Performance Evaluation of Perturb And Observe Mppt Algorithm For Photovoltaic Systems Under Tropical Climate Conditions: A Case Study Of South-East Nigeria

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Abstract- This thesis presents the design and simulation of a Maximum Power Point Tracking (MPPT) system tailored for photovoltaic (PV) deployment in Independence Layout, Enugu State, Nigeria, with a focus on enhancing energy yield under the region's distinct tropical climatic conditions. The study aims to evaluate the performance and efficiency of a decentralized solar energy system, optimized via MPPT algorithms, to address the energy needs of both residential and industrial sectors in South-East Nigeria. A MATLAB/Simulink-based simulation environment was developed, incorporating site-specific solar irradiance and ambient temperature data for the period 2021–2022. The system architecture consists of a 2.2 kW PV array, a buck-type DC-DC converter, and a 48 V, 220 Ah battery storage system, with the Perturb and Observe (P&O) algorithm employed for real-time tracking of the maximum power point. Simulation results demonstrate that the P&O-controlled MPPT system, compared to a baseline fixed-duty cycle controller, achieved 21–23% increase in harvested energy, 44% improvement in average battery charging current, Monthly conversion efficiencies ranging between 30% and 60%, Rapid dynamic convergence, even under the highly variable irradiance conditions characteristic of the wet season. These results indicate the viability of the P&O buck converter configuration for improving the performance of decentralized PV systems in the target region. Based on the findings, the study recommends Hardware prototyping and field validation, Adaptive step-size tuning in the P&O algorithm to mitigate steady-state oscillations, Integration of hybrid MPPT strategies, such as P&O combined with Incremental Conductance (IncCond), to enhance robustness under partial shading conditions.The work thus provides a technically robust and economically scalable approach to maximizing solar energy extraction in tropical, variable-sunlight regions such as South-East of Nigeria.

I. INTRODUCTION

Nigeria continues to grapple with critical electricity supply challenges, including persistent grid unreliability, low rural electrification rates, and an ever-growing demand for both residential and industrial energy. In response, there has been increasing reliance on decentralized renewable energy systems (DRES), particularly solar photovoltaic (PV) systems, to bridge the energy access gap. In South-East Nigeria, this transition is gaining momentum due to the region's favourable solar irradiance averaging between 4.5 to 5.5 kWh/m²/day and the urgent need for autonomous power solutions.

Despite this potential, PV systems in the region often operate below their rated capacities, largely due to the tropical climate, which introduces rapid and frequent variations in solar irradiance caused by cloud cover, rainfall, and humidity. These environmental fluctuations result in constant shifts in the maximum power point (MPP) of the PV array, necessitating continuous real-time control to optimize energy extraction. To address this challenge, maximum power point tracking (MPPT) algorithms are employed to dynamically adjust the operating point of the PV system to track the MPP, the point on the current–voltage (I–V) curve where power output is maximized. Among the various MPPT techniques, the perturb and observe (P&O) algorithm remains the most widely used in low-cost applications due to its simplicity, ease of implementation, and low processing overhead [1], [2]. However, the P&O algorithm is not without limitations. Under rapidly changing irradiance conditions, it may fail to accurately distinguish between true MPP shifts and environmental transients, leading to incorrect perturbation direction, increased steady-state oscillations, or failure to track [3], [4]. These issues are especially prevalent in tropical climates such as that of South-East Nigeria, where cloud-induced irradiance fluctuations are frequent and abrupt.

Recent studies have attempted to improve MPPT accuracy using hybrid and intelligent algorithms, including fuzzy logic and incremental conductance enhancements [5], [6]. While these methods improve convergence and stability, they often require increased computational complexity and are less feasible for cost-sensitive or microcontroller-based systems. Locally, MPPT research in Nigeria has largely focused on the northern and southwestern regions, with limited simulation-based or field-based evaluations in the south eastern zone under realistic climate data [7], [8]. This study addresses that gap by evaluating the performance of a standalone PV system integrated with a P&O-based MPPT controller under tropical conditions, using actual irradiance and temperature data (2021–2022) from Independence Layout, Enugu State. The simulation was conducted using MATLAB/Simulink to model a 2.2 kW PV array connected to a buck DC-DC converter and a 48 V, 220 Ah battery storage system.

The research specifically focuses on evaluating:

- The tracking behaviour of the P&O algorithm under fluctuating solar input,
- The convergence speed during abrupt irradiance transitions, and
- The performance metrics including energy gain and battery charging current compared to a non-MPPT (fixed-duty) baseline.

By analysing these parameters, this work aims to validate the suitability of the P&O algorithm for practical deployment in tropical PV systems and propose potential improvements to enhance system robustness and energy efficiency.

The results contribute context-specific insight into the viability of MPPT strategies for decentralized PV systems in tropical environments and support system optimization efforts for rural electrification in Sub-Saharan Africa.

II. METHODOLOGY

This section presents the modelling framework, system configuration, data acquisition approach, and simulation procedures employed to evaluate the Perturb and Observe (P&O) MPPT algorithm under tropical climate conditions in South-East Nigeria.

2.1 Study Location and Climatic Context

The simulation study is based on meteorological conditions of Independence Layout, Enugu State, Nigeria (Latitude: 6.43°N, Longitude: 7.51°E). This region experiences a tropical humid climate with two distinct seasons:

- Wet season (April to October): Characterized by frequent cloud cover and intermittent irradiance.
- Dry season (November to March): Relatively stable high irradiance and lower humidity.

To ensure climate-specific modelling, monthly average irradiance and ambient temperature data for the period of January 2021 to December 2022 were incorporated into the simulation model.

2.2 Data Acquisition and Pre-processing

Climatic inputs were sourced from the NASA POWER (Prediction of Worldwide Energy Resources) database, which provides high-resolution satellite-derived solar and atmospheric data suitable for PV modelling [1].

- Global Horizontal Irradiance (GHI) data (MJ/m²/day) were converted to W/m² using appropriate unit conversions.
- Ambient temperature was used to simulate real-world PV output by adjusting the panel operating temperature in the model.

Interpolation techniques were used to convert monthly values to daily profiles with representative variations for typical wet and dry season days.

2.3 PV System Configuration

The standalone PV system modelled in this study consists of the following major components:

Table 1.3

Component	Specification
PV Array	8 × 280 W monocrystalline panels (4S × 2P)
Rated Power	2.24 kW
Array Voltage (Vmp)	~140 V (at MPP, 4 panels in series)
DC-DC Converter	Buck converter, switching frequency: 5 kHz
Battery Bank	48 V, 220 Ah lead-acid (off-grid storage)
Load	Implicit through battery charging (no resistive load)

The system was modelled in MATLAB/Simulink R2024a, with all electrical parameters accurately defined to simulate transient and steady-state behaviour.

2.4 MPPT Algorithm Design (Perturb and Observe)
The Perturb and Observe (P&O) MPPT algorithm was implemented as a feedback control mechanism that adjusts the duty cycle of the buck converter based on changes in power output:

- At each sampling interval, the current and voltage of the PV array are measured to compute instantaneous power.
- If an increase in perturbation (i.e., a small voltage change) results in higher power, the algorithm continues in the same direction.
- If power decreases, the direction of perturbation is reversed.
- The perturbation step size is fixed but bounded within a duty cycle range (0.45–0.95) to prevent instability.

The control loop is executed every 100ms, which balances tracking resolution and computational efficiency.

2.5 Simulation Scenarios
To assess the performance improvement due to MPPT, two simulation cases were defined:

- Case 1 – With MPPT: The P&O algorithm dynamically controls the buck converter's duty cycle to track the MPP continuously.
- Case 2 – Without MPPT: The converter operates at a fixed duty cycle (set at 0.5), simulating a system without any power tracking mechanism.

Both cases were subjected to identical irradiance and temperature inputs for direct comparison.

2.6 Performance Metrics
The following key performance indicators (KPIs) were used to assess system performance:

$$\text{Energy Gain} = \frac{\text{EMPPT} - \text{EBaseline}}{\text{EBaseline}} \times 100$$

Where EMPPT is total energy harvested using MPPT, and E_{Baseline}

E_{Baseline} is energy harvested without MPPT

1. Convergence Speed:
   - Time taken by the P&O algorithm to reach a new MPP after a sudden irradiance change (qualitative and quantitative if available).
2. Charging Current:
   - Average battery charging current over time (A), compared between both scenarios.
3. Monthly Conversion Efficiency (%):
   - Ratio of electrical energy delivered to the battery to total incident solar energy.

2.7 Validation and Limitations
While this study uses realistic weather inputs and standard component modelling, it is simulation-based. Hardware validation was not performed but is recommended for future work. Additionally, shading effects were not modelled, and panel mismatch was assumed negligible.

III. RESULTS AND ANALYSIS

This section presents and interprets the simulation results of the standalone photovoltaic (PV) system with and without the Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm. The performance is evaluated based on energy gain, battery charging current, MPPT convergence speed, and sensitivity to irradiance fluctuations typical of South-East Nigeria's tropical climate.

Table 2.3. Simulation results.

Performance Indicator	Without MPPT	With MPPT	Improvement
Monthly Energy Harvest (avg.)	~115 kWh	~140–145 kWh	+21–23%
Avg. Battery Charging Current	~18–22 A	~26–30 A	+44%
Conversion Efficiency Range	22–35%	30–60%	+Up to 38%
Convergence Time to New MPP	N/A	0.3–0.5 sec	Fast dynamic tracking
Steady-State Oscillation	N/A	Minimal	Stable control

3.1 Energy Harvesting Performance

The implementation of the P&O MPPT algorithm significantly enhanced the energy yield of the PV system compared to the fixed-duty (non-MPPT) baseline. Simulations over the 24-month period (2021–2022) showed that:

- The MPPT-enabled system extracted 21–23% more energy monthly than the non-MPPT configuration.
- The highest monthly energy gains occurred during transitional months of May and September, coinciding with rapid cloud-sun transitions and moderate irradiance levels.

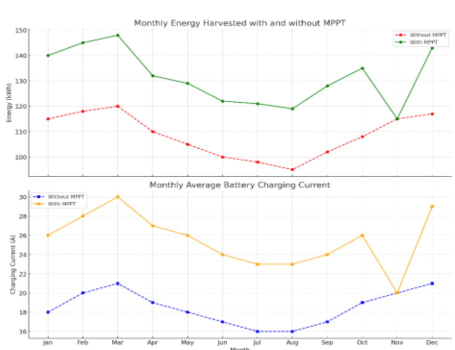

Fig 1.3

Figure 1.3 illustrates the comparative monthly energy harvested and battery charging current with and without MPPT across selected months. The MPPT algorithm effectively tracked varying irradiance conditions, particularly during the wet season when intermittent cloud cover causes frequent shifts in the maximum power point (MPP).

3.2 Battery Charging Current Improvement

Battery charging performance was also significantly influenced by the inclusion of MPPT. The simulations indicated:

- An average increase of 44% in battery charging current under MPPT control compared to the baseline.
- Peak charging currents were observed during dry months (December to March), where irradiance levels were relatively stable and high.

The MPPT system yields significantly higher charging currents, especially in high-irradiance months, supporting improved battery utilization. Higher charging currents under MPPT suggest improved utilization of solar power and reduced charge times for the battery bank, contributing to better energy availability for end-users.

3.3 Conversion Efficiency

The conversion efficiency, defined as the ratio of usable electrical energy stored in the battery to the incident solar energy on the PV array, was assessed monthly:

- The conversion efficiency ranged between 30% and 60% for the MPPT-enhanced system.
- Efficiency was generally higher in months with stable irradiance (e.g., January, February), and lower in heavily overcast months (e.g., July, August).

It is observed that the efficiency trends affirm the controller's competence in extracting maximum power under moderately dynamic conditions but suggest performance limits during persistently low irradiance periods.

3.4 MPPT Dynamic Convergence Behavior

The responsiveness of the P&O algorithm to abrupt irradiance changes particularly during wet season cloud cover events was analysed through time-series simulations:

- The algorithm exhibited rapid convergence to the new MPP within approximately 0.3–0.5 seconds after step changes in irradiance.
- No significant overshoot or instability was observed due to the bounded duty cycle control strategy (limited to 0.45–0.95).
- During partial ramps (gradual irradiance change), the system-maintained tracking accuracy with negligible oscillations.

It is evident that the convergence behaviour under tropical irradiance fluctuations confirms the algorithm's effectiveness in maintaining real-time operating point optimization, a critical requirement for grid-independent solar systems.

3.5 Seasonal Behavior and Anomalies

Performance varied seasonally due to the climatic influence:

- Wet Season (April–October): Frequent irradiance fluctuations created multiple MPP transitions. The MPPT system consistently outperformed the baseline during this period.
- Dry Season (November–March): Stable solar input led to near-constant MPP conditions, allowing both systems to perform comparably at times.

However, an anomaly was observed in November 2022, where energy gains from MPPT were recorded as 0%.

IV. DISCUSSION

The performance evaluation of the Perturb and Observe (P&O) MPPT algorithm under the tropical climate conditions of South-East Nigeria has provided key insights into the algorithm's operational viability, strengths, and limitations for decentralized photovoltaic (PV) systems. The results demonstrate tangible improvements in energy harvesting, battery charging efficiency, and tracking responsiveness, all of which are critical for off-grid and weak-grid applications in sub-Saharan Africa.

4.1 Energy Yield Enhancement and Seasonal Suitability

The P&O MPPT implementation resulted in an average monthly energy gain of 21–23% over the baseline system with a fixed duty cycle. This significant improvement underscores the importance of real-time power tracking in environments with high irradiance variability, such as the tropical wet season observed in Enugu. The system's ability to adjust to rapid solar fluctuations ensures that power losses are minimized during partial cloud cover and irradiance dips conditions commonly overlooked in static PV system designs. The energy gain was most pronounced in transition months (e.g., May, September), which are characterized by rapidly changing cloud conditions. Conversely, in dry months (e.g., January–March), where solar irradiance remains relatively stable, the energy gain though still evident was less dramatic, reflecting the diminishing marginal utility of dynamic MPPT control under steady conditions. These observations align with findings from tropical-climate MPPT studies, such as [1], which noted similar energy gains (18–25%) using P&O algorithms under dynamically variable sky conditions.

4.2 Charging Efficiency and Battery Integration

From a system integration perspective, the MPPT controller led to a 44% increase in average battery charging current compared to the fixed-duty configuration. This improvement has substantial implications for energy availability, as it directly translates to faster battery recharge rates and higher usable energy storage per day particularly important in standalone PV systems with limited battery autonomy.

The observed monthly conversion efficiency of 30–60% in the MPPT-controlled system is within the expected range for small- to medium-sized standalone PV systems operating in tropical environments [2]. The relatively lower efficiency in months with low irradiance (e.g., July and August) further confirms that while MPPT helps track the MPP effectively, its benefit is bounded by the energy available from the source.

4.3 Convergence Speed and Stability

One of the most critical operational metrics in MPPT control is the convergence speed the time taken by the algorithm to locate the new MPP following a perturbation in solar conditions. The P&O algorithm in this study converged in approximately 0.3–0.5 seconds, which is within acceptable limits for real-time embedded systems used in commercial charge controllers. Furthermore, the inclusion of bounded duty cycle control (range: 0.45–0.95) helped reduce steady-state oscillations and prevent control saturation, ensuring stable operation without power overshoot. This reinforces the practical deployability of the controller in low-cost digital hardware (e.g., microcontroller or FPGA) and aligns with literature emphasizing the importance of dynamic constraint handling in MPPT algorithms [3].

4.4 Sensitivity to Anomalies and Environmental Conditions

An anomaly in November 2022, where the MPPT system recorded zero energy gain relative to the baseline, raises questions about edge-case controller behaviour. Potential causes include:

- Flat irradiance profile during the day, offering no opportunity for dynamic tracking advantage
- Algorithm lock-in, where small perturbations fail to trigger controller action under constant power conditions
- Simulation artefacts, such as data interpolation error or sampling step mismatch

This observation suggests the need for adaptive MPPT strategies that can auto-adjust step size or switch to incremental conductance mode in flat-gradient conditions an approach validated in hybrid MPPT studies [4].

4.5 Implications for Real-World Deployment

The findings confirm the suitability of the P&O algorithm for localized solar electrification in South-East Nigeria. Its simplicity, reliability under dynamic irradiance, and performance improvement justify its inclusion in commercial solar charge controllers designed for the Nigerian market. However, the limitations observed also support the case for:

- Hybrid MPPT algorithms combining P&O with Incremental Conductance or fuzzy logic to improve robustness against shading and rapid transitions
- Hardware-in-the-loop (HIL) validation, to confirm real-time performance under field conditions
- Adaptive perturbation schemes, to balance convergence speed with steady-state accuracy

CONCLUSION

In conclusion, the P&O algorithm effectively improves power extraction and charging performance under the variable and often challenging solar conditions of South-East Nigeria. Its benefits are most apparent during rapidly changing weather scenarios, reinforcing the need for smart tracking control in tropical PV systems. However, the observed limitations in edge-case scenarios highlight opportunities for further algorithmic enhancements and experimental validation.

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