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High-Performance Numerical MPPT for Sustainable and Economical PV Systems

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***Abstract*—This study proposes a novel maximum power point tracking (MPPT) algorithm for photovoltaic (PV) systems, employing numerical analysis techniques to enhance energy harvest, reduce environmental impact, and improve economic feasibility. Conventional MPPT methods commonly suffer from limitations when operating under changing dynamic conditions. To address these challenges, this paper proposes a new MPPT algorithm based on the secant numerical method. The proposed method is based on a detailed model to calculate and estimate the maximum power point based on feedback from solar radiation and temperature. The proposed algorithm demonstrates superior performance. It achieves significantly higher energy harvest, faster response times, and greater potential for CO_2 emissions avoidance. Furthermore, it exhibits exceptional stability during rapid irradiance fluctuations compared to conventional techniques, such as Perturb and Observe and Incremental Conductance, as well as the Predict and Correct method. In addition, economic analysis emphasizes the potential for a substantial increase in revenue when the proposed method is used over long periods.**

***Keywords*—Maximum Power Point Tracking (MPPT), Numerical Analysis, Secant Method, Photovoltaic (PV) Systems, Renewable Energy Sources (RESs), Solar Energy, Model-Based Control, Perturb and Observe (P&O), Incremental Conductance (INC), Predictor-Corrector MPPT (PredCorr), artificial intelligence (AI), CO_2 Emissions, Economic Analysis**

I. Introduction

Recently, Renewable Energy Sources (RESs) have been widely utilized to achieve sustainable development goals [1]. The International Energy Agency (IEA) views solar power plants as a crucial factor in shaping a more sustainable energy future [2]. Photovoltaic (PV) systems are attractive solutions for addressing escalating energy demands due to their reliance on a plentiful, emissions-free resource and their relatively low operational costs [1]. However, the efficiency of PV systems is inherently constrained by environmental fluctuations, such as irradiance and temperature, which affect the operating point of solar panels. In order to optimize the benefits of PV systems, Maximum Power Point Tracking (MPPT) algorithms are utilized to enhance system efficiency and stability [3].

Conventional MPPT methodologies, such as Perturb and Observe (P&O) and Incremental Conductance (INC), have been extensively adopted due to their simplicity and ease of implementation [4]. Moreover, these methods have several challenges, including oscillations around the MPP, slow convergence speed, and reduced tracking efficiency, especially under rapidly changing environmental conditions [5]–[8].

An illustration of this methodology is P&O, which is significantly responsible for oscillations around the MPP. Consequently, losses in power and efficiency will occur [7]. The other methodology, INC, was employed to resolve this issue. Nevertheless, the response remains slow under dynamic conditions and may not be capable of tracking the MPP [6].

In addressing the limitations of conventional methodologies, a significant focus has emerged on the exploration of optimization-based algorithms [9]. It has been demonstrated that methods such as particle swarm optimization (PSO) have improved effectiveness in identifying the global MPP, especially under rapidly changing environmental factors. While these algorithms facilitate accelerated convergence and enhanced accuracy, they can concomitantly escalate computational expense, thereby posing a substantial challenge in practical applications [9].

The integration of artificial intelligence (AI) has had a significant impact on the enhancement of MPPT methodologies [10]. It has been demonstrated that techniques such as artificial neural networks (ANNs) exhibit remarkable adaptability and precision in predicting and tracking the MPP under varying environmental conditions. These AI-driven approaches effectively manage the nonlinearities and uncertainties characteristic of PV systems. However, the implementation of these methods typically requires substantial training datasets and greater computational resources, which may limit their practicality in certain applications [11], [12].

The integration of conventional algorithms with artificial intelligence or optimization is referred to as hybrid MPPT. For instance, PSO-P&O hybrids integrate global search capabilities with local optimization, thereby attaining enhanced tracking speed and consistent performance in comparison to individual methods. However, the integration of these strategies increases design complexity, leading to the necessity of meticulous optimization for practical implementation [12], [13].

These advancements have led to the emergence of numerical analysis methods as a promising avenue for further enhancing MPPT algorithms. By leveraging mathematical modeling and numerical optimization, these techniques enhance the robustness and adaptability of MPPT strategies, enabling PV systems to achieve higher efficiency even under rapidly fluctuating environmental conditions [14]–[16].

Lyu et al. [16] presented the Predictor-Corrector MPPT method, which employs numerical analysis techniques to predict and correct. Nevertheless, this method remains less efficient due to its neglect of specific properties of the solar cell and its reliance on initial estimations of voltage and current values.

To provide further clarification on the innovation and efficacy of the proposed method in comparison to both conventional and state-of-the-art techniques, a more detailed discussion is presented below.

Unlike contemporary methods that depend on simplified models or static assumptions—such as ignoring series resistance (R_s) or employing fixed voltage guesses—our proposed solution implements a dynamic mathematical model of the PV cell. This model incorporates precise, real-time irradiance and temperature measurements to enable predictive MPP estimation. While prior work, such as Lyu et al. in 2024 [16], applies a basic predictor-corrector structure, our technique employs an enhanced secant-based numerical formulation that demonstrates significant improvement over current state-of-the-art MPPT algorithms. The innovative combination of dynamic modeling, sophisticated numerical analysis, and comprehensive performance validation represents the fundamental contribution of this research.

The present study not only identifies the limitations of the current approach but also proposes a potential solution. The proposed MPPT method, based on numerical analysis and utilizing a method, aims to enhance energy harvesting and ensure that the PV system operates at the optimal power point under dynamically changing conditions. This research is urgent and has the potential to impact the future of PV systems significantly.

This study demonstrates considerable promise for practical applications. The numerical analysis-based MPPT method has the potential to enhance energy harvesting and reduce carbon dioxide emissions significantly. Moreover, it is expected to yield economic benefits, making it a promising choice for PV systems compared to alternative methods.

The structure of this paper is as follows: Section II presents the methodology, detailing the PV system model and the numerical technique. The third section of the paper presents and discusses the results, focusing on the energy harvested, time response, CO_2 emission and economic analysis. Finally, the conclusions of the paper are set out in Section IV.

II. Methodology

This section outlines the methodology used to develop and evaluate a novel numerical analysis-based MPPT algorithm. The approach focuses on creating a robust and accurate MPPT algorithm that ensures optimal power output under varying environmental conditions.

A. Photovoltaic (PV) System

The PV system is modeled using a single-diode equivalent circuit, as illustrated in Fig. 1.The current (I) of the PV system is given by (2) [4], while the power output (P) is calculated as the product of current and voltage using (1) [3].

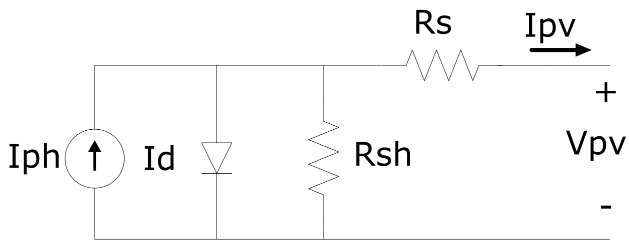

Fig. 1. Equivalent model of PV array

$$P_{pv} = V_{pv} \times I_{pv} \tag{1}$$

where P_{pv} is output power of PV array (Watts, W), V_{pv} is output voltage of the PV array (Volts, V) and I_{pv} is output current of the PV array (Amperes, A)

$$I_{pv} = I_{\text{ph}} - I_0 \left[\exp\left(\frac{V_{pv} + I_{pv}R_s}{aV_t}\right) - 1\right] - \frac{V_{pv} + I_{pv}R_s}{R_{\text{sh}}} \tag{2}$$

where I_{ph} is photo-generated current (A), I_0 is saturation current of the diode (A), R_s is series resistance of the PV cell (ohms, Ω), R_{sh} is shunt resistance of the PV cell (Ω), a is diode ideality factor, V_t is thermal voltage , defined as $V_t = \frac{kT}{q}$ (Volts, V), where:

- k: Boltzmann constant (1.38×10^{-23} J/K).
- T: Absolute temperature (kelvins, K).
- q: Elementary charge of an electron (1.6×10^{-19} C).

The photo-generated current is calculated using (3) [3].

$$I_{\text{ph}} = [I_{\text{ph,ref}} + \alpha(T - T_{\text{ref}})] \times \frac{G}{G_{\text{ref}}} \tag{3}$$

where $I_{\text{ph,ref}}$ is reference photo-generated current (amperes, A) at the reference temperature T_{ref} and reference irradiance G_{ref}, α: is temperature coefficient of the photo-generated current (A/K), T is actual cell temperature (K), T_{ref} is reference cell temperature (K), G is actual irradiance on the cell surface (W/m^2) and G_{ref} is reference irradiance (typically $1000\,\text{W/m}^2$).

This model accounts for variations in environmental conditions, including irradiance and temperature, which directly impact PV system performance.

B. Numerical Analysis Method

MPP is determined by numerically solving for the point where power is maximized, or where the power derivative with respect to voltage equals zero. The solution employs the Secant method, an iterative root-finding algorithm chosen because it does not require calculating the power function's derivative, a significant advantage for practical implementation. The Secant method uses previous voltage estimates (V_{k-1} and V_k) to compute the next voltage estimate (V_{k+1}) , as demonstrated in (4) [16].

$$V_{k+1} = V_k - P'(V_k) \times \frac{V_k - V_{k-1}}{P'(V_k) - P'(V_{k-1})} \tag{4}$$

- V_k: Voltage at the k-th iteration (V).
- V_{k-1}: Voltage at the $(k-1)$-th iteration (V).
- $P'(V)$: The derivative of power with respect to voltage, i.e., $P'(V) = \frac{dP}{dV}$.

The algorithm iteratively updates the voltage until the power curve's derivative approaches zero or the power change between iterations falls below a predefined threshold, indicating the MPP.

C. Proposed MPPT Algorithm

The implementation of the proposed MPPT algorithm follows the steps outlined below, with the corresponding flow chart illustrated in Fig. 2

- **Initialization**
  - Set initial operating voltage (V_o).
  - Define convergence threshold (μ).
- **Iteration**
  - Calculate current (I_k), voltage (V_k), and power ($P_k = V_k \times I_k$).
  - Calculate derivative (P'_k) using previous values.
  - Update voltage using the Secant method.
- **Convergence Check**
  - Verify if $|P_{k+1} - P_k| < \mu$.
  - If the condition is met, stop; otherwise, repeat the iteration.

D. Simulation Setup

The proposed MPPT algorithm and comparative traditional methods were simulated using MATLAB/Simulink. The simulation model, as illustrated in Fig. 3, integrates a 100-kW PV array, a DC-DC converter, an inverter, and an AC grid connection. The PV array consists of 66 parallel strings, each comprising 5 series-connected PV modules. The PV array converts solar radiation into electrical energy, which is then optimized by the DC-DC converter using the MPPT algorithms. Finally, the inverter transforms the DC power into AC power for distribution to the grid, which is modeled as a standard three-phase utility network with a nominal line-to-line voltage of 400 V and a frequency of 50 Hz.

The simulation utilized a solar module of the SunPower SPR-305E-WHT-D type, with its specifications outlined in Table I.

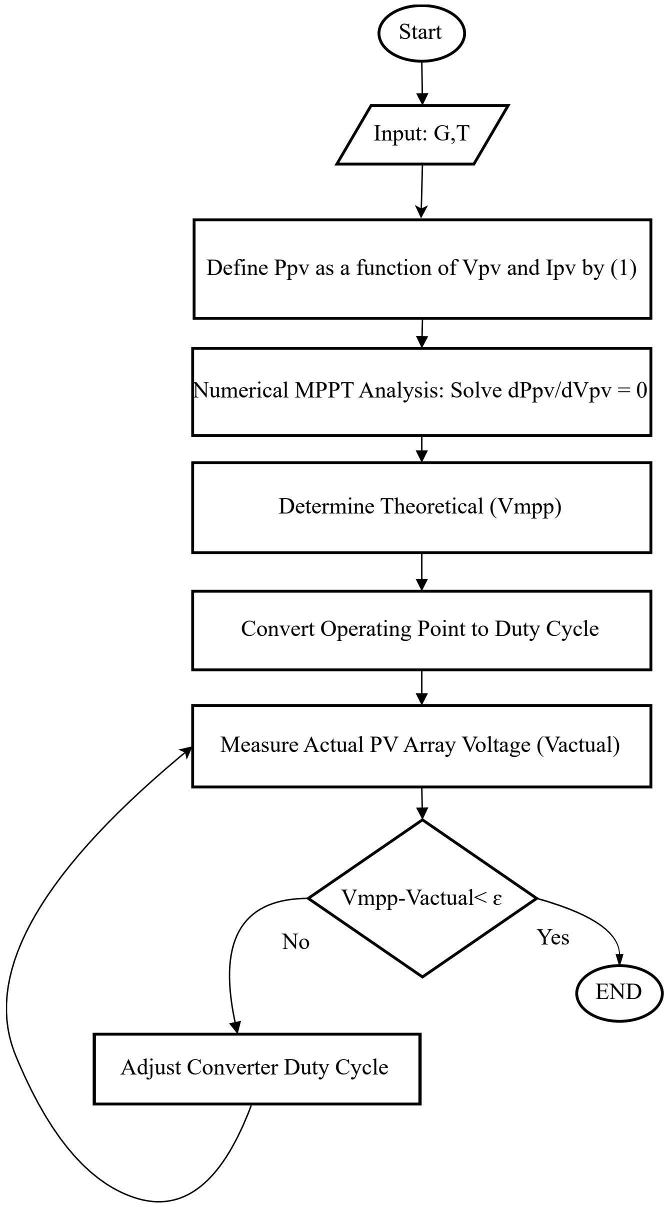

Fig. 2. proposed MPPT flow chart

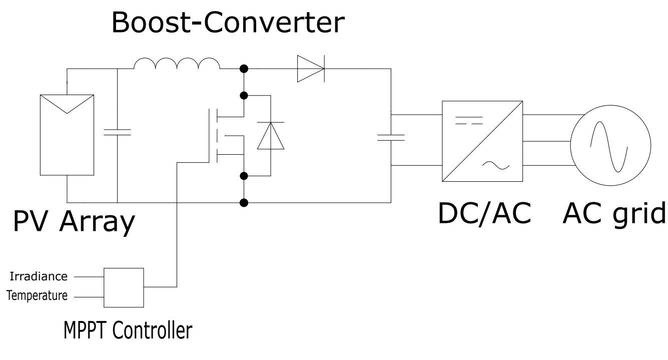

Fig. 3. PV system block diagram

The simulations were conducted under two scenarios:

TABLE I
ELECTRICAL CHARACTERISTICS OF SUNPOWER SPR-305E-WHT-D MODULE, STRING (NS = 5), AND ARRAY (NP = 66)

Parameter Value per	Module	String	Array	Unit
Maximum Power (P_{max})	305	1525	100,650	W
Open-Circuit Voltage (V_{oc})	64.2	321.0	321.0	V
Short-Circuit Current (I_{sc})	5.96	5.96	393.36	A
Voltage at MPP (V_{mp})	54.7	273.5	273.5	V
Current at MPP (I_{mp})	5.58	5.58	368.28	A

- **Constant Conditions**: Fixed irradiance ($1000\,\mathrm{W/m^2}$) and temperature (25°C).
- **Variable Conditions**: Temperature range of 15°C to 44°C and irradiance fluctuation between $0\,\mathrm{W/m^2}$ and $1000\,\mathrm{W/m^2}$.

III. RESULTS AND DISCUSSION

This section will discuss and compare the performance of the results for the four MPPT algorithms: P&O, INC, PredCorr, and the proposed method. The evaluation encompasses the presentation of results and their subsequent discussion. These results include the energy harvested and the response time under constant conditions, the energy harvested and CO_2 emissions under variable conditions, and the overall economic evaluation on a monthly and yearly basis.

A. Performance Under Constant Conditions

The fundamental performance of the MPPT algorithms was evaluated under a controlled environment of constant irradiance ($1000\,\mathrm{W/m^2}$) and temperature (25°C). These steady-state conditions enabled a clear comparison of each algorithm's inherent characteristics without external fluctuations. Fig. 4 presents the power output curves for all four methods under these constant conditions. The analysis demonstrated that the numerical analysis method exhibited superior performance, rapidly attaining the MPP while sustaining consistent output.

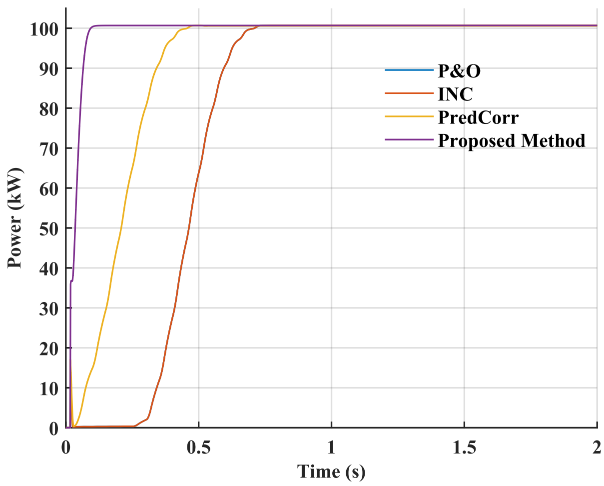

Fig. 4. Maximum Power Output from Solar Panels at ($1000\,\mathrm{W/m^2}$) and (25°C): Comparison of Different MPPT Controllers

Table II shows the total energy harvested and the response time of each method under constant conditions. As is evident, the numerical analysis method achieves the highest energy harvest of 54.88 Wh and the lowest response time of 107 milliseconds.

TABLE II
ENERGY HARVEST AND RESPONSE TIME FOR MPPT METHODS (CONSTANT CONDITIONS)

Name of Method	Energy(wh)	Response Time (ms)
P&O	42.89	724
INC	42.89	724
PredCorr	50.798	473
Proposed method	54.88	107

The numerical analysis method has been demonstrated to exhibit significantly faster responsiveness than other methods, as evidenced by its remarkably low response time of 107 ms under constant conditions. This faster responsiveness allows the method to quickly adapt to sudden changes, thereby minimizing energy loss during transient periods. In comparison to P&O and Incremental Conductance, the numerical analysis method achieves 21.8% higher energy harvesting, and 8.1% more than PredCorr. This suggests that the Numerical Analysis method not only optimizes energy harvest but also responds more rapidly to reach the MPP.

B. Performance Under Variable Conditions

To evaluate the dynamic performance of the MPPT algorithms under realistic operating conditions, a simulation was conducted with variable irradiance and temperature profiles as shown in Fig. 5. Fig. 6 presents the power output curves for all four methods under these variable conditions. It has been demonstrated that the numerical analysis method yields a higher power output, whereas the other techniques exhibit varying degrees of instability and oscillation. The utilization of conventional methodologies, such as P&O and INC, is susceptible to fluctuations around the MPP. These methodologies can become trapped in local maxima, particularly under conditions of non-uniform irradiance. Additionally, the PredCorr method disregards the series resistance of the PV array during the modification of the flow chart. The selection of the initial guess for this method exerts an influence on the MPP. Table III shows a comparison of the total energy harvested and estimated CO_2 emissions avoided for each method.

TABLE III
ENERGY HARVEST AND AVERTED CO_2 EMISSIONS FOR MPPT METHODS (VARIABLE CONDITIONS)

Name of Method	Energy (kwh)	Averted CO_2 emissions (kg)
P&O	45.71	8.91
INC	22.21	4.33
PredCorr	46.66	9.09
Proposed method	56.89	11.09

The superior performance of the Numerical Analysis method under variable conditions demonstrates its robustness and adaptability to changing environmental factors, which

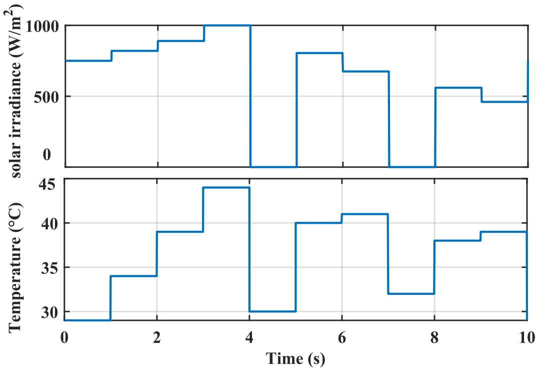

Fig. 5. Solar Irradiance and Temperature Profiles Used in Simulation: Inputs to Solar Panels

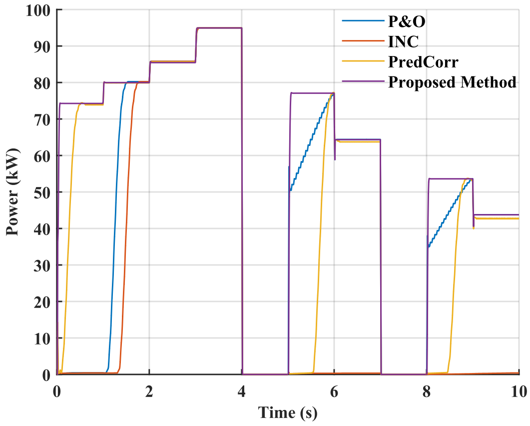

Fig. 6. Maximum Power Output from Solar Panels Under Varying Temperature and Irradiance Conditions: Comparison of Different MPPT Controllers

is crucial for real-world solar PV applications. Based on Spain's 2022 electricity sector emissions factor (0.195 kg CO_2 eq/kWh) [17], the Numerical Analysis method potentially avoided 11.09 kg of CO_2 emissions. This represents a 24.5%, 156.1%, and 22.0% improvement over the P&O, Incremental Conductance, and PredCorr methods, respectively. This demonstrates the significant impact and cost savings of our novel approach. The Environmental Impact Assessment indicates that the environmental benefits of enhanced MPPT algorithms extend beyond mere efficiency metrics. The simulation test demonstrates that we can reduce CO_2 emissions as much as some of the most efficient farms.

The effectiveness of our model-based approach in calculating the MPP is particularly noteworthy. By establishing relationships between PV system parameters, temperature, and irradiance, the model accurately predicts the voltage at the MPP and estimates system power. The integration of solar irradiance and temperature sensors enhances the adaptability of the method to different PV cell types, potentially contributing to improved reliability and sustainability of renewable energy systems.

C. Economic analysis of energy harvesting

Economic analysis was performed extensively to evaluate the financial impact of implementing different MPPT methods. As the energy production rate is low in the INC method, it was adopted as the primary reference. The analysis was conducted under standard operating conditions in Spain, which include 208 hours of sunshine per month and 2,500 hours of sunshine per year, with a production cost of €0.19 per kilowatt-hour [18].

As illustrated in Table IV, a comparative analysis of energy production and revenue generation is conducted on a monthly and annual basis, utilizing various methodologies. The study reveals a notable disparity in the revenue values generated by the proposed numerical analysis method in comparison to alternative approaches. For instance, the process exhibits a €5,310.50 annual saving when compared to P&O, and a €4,859.25 annual saving when contrasted with PredCorr. These disparities and values signify significant economic prospects that can be capitalized upon to achieve operational efficiency and cost-effectiveness in energy production systems.

TABLE IV
ESTIMATED POWER GENERATED AND REVENUE FROM TESTS WITH SOLAR IN SPAIN FOR DIFFERENT METHODS.

MPPT	kWh/Month	Revenue(€)	kWh/Year	Revenue(€)
INC	0	0	0	0
P&O	4888	928.72	58750	11,162.50
PredCorr	5085.6	966.26	61125	11,613.75
Proposed	7213.4	1,370.55	86700	16,473

A comparative analysis of the four methods confirms that the proposed numerical analysis method achieves higher energy savings and provides significant financial benefits. Furthermore, the annual and monthly savings from this method can be reinvested in system expansions, thereby enhancing its economic feasibility.

This study provides definitive evidence of the efficacy of the proposed numerical analysis method in enhancing energy production processes and reducing carbon dioxide emissions under rapidly varying environmental conditions. A meticulous examination of the comprehensive economic data presented in Table IV reveals that the proposed method leads to an augmentation in revenue generation in practical applications.

IV. CONCLUSION

In this study, a novel MPPT algorithm was proposed. This algorithm utilizes numerical analysis techniques, particularly the Secant method. The proposed method involves the iterative calculation and estimation of MPP using a model-based approach, with the incorporation of feedback from solar radiation and temperature. Simulation results demonstrate that the proposed method outperforms conventional MPPT techniques (P&O, INC) and PredCorr methods in key performance indicators. The proposed algorithm has been demonstrated to enhance tracking efficiency, thereby leading to a substantial augmentation in energy harvest, particularly in variable environmental conditions. Its rapid convergence and response times contribute to a reduction in energy dissipation during transient phases. It is imperative to note that an augmentation in energy production results in a diminution of CO_2 emissions, as compared to alternative methodologies. In addition, the economic analysis results indicate a considerable potential for augmented revenue generation when employing the proposed algorithm, thereby further enhancing its economic viability.The simulation results corroborate the significance of integrating advanced numerical analysis techniques into MPPT systems. The proposed method has the potential to enhance the technical performance of PV systems, thereby increasing their economic viability and contributing to their environmental impact.

Future research should prioritize the practical application of the proposed algorithm and its evaluation under various realistic environmental conditions. It is recommended that further research be conducted in order to explore advanced numerical analysis with other renewable energy systems. In addition, it is recommended that the aforementioned analysis be comprehensively tested for sensor accuracy and real-world variations under various operational scenarios.

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