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Comparison of P&O and Incremental Conductance for MPPT Algorithm in Bifacial Solar PV System

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Abstract: *Maximum Power Point Tracking (MPPT) is a critical component of photovoltaic (PV) systems, as it enables maximum power extraction from PV modules under varying environmental conditions. This study presents a comparative performance analysis of the Perturb and Observe (P&O) and Incremental Conductance (INC) MPPT algorithms implemented with a boost converter through duty-cycle control. A 315 Wp PV module is considered for evaluating the tracking performance of both algorithms under standard and dynamic operating conditions. Under standard test conditions, the system is evaluated at an irradiance of 1000 W/m² and a temperature of 25°C, while dynamic conditions are introduced through variations in solar irradiance. The performance of both MPPT techniques is assessed using absolute power error, Mean Absolute Percentage Error (MAPE), tracking efficiency, and dynamic response characteristics. Under standard operating conditions, the P&O method achieves a MAPE of 6.6%, compared with 13.9% for the INC method, indicating better tracking stability and lower error. However, under dynamic irradiance conditions, the INC method demonstrates superior performance, achieving a MAPE of 20.87%, whereas the P&O method records a considerably higher MAPE of 37.26%. The results indicate that P&O provides more stable tracking under relatively constant irradiance, whereas INC offers improved adaptability to rapidly changing environmental conditions. Therefore, the selection of an appropriate MPPT technique depends strongly on the operating environment and irradiance variability. The comparative findings provide useful insights for selecting suitable MPPT algorithms for efficient and reliable photovoltaic power conversion systems.*

Keywords: Maximum Power Point Tracking (MPPT); Perturb and Observe (P&O); Incremental Conductance (INC); Photovoltaic (PV) Systems; Mean Absolute Percentage Error (MAPE).

I. INTRODUCTION

Bifacial solar PV systems have achieved widespread usage today and are viewed as a highly effective solution for improving the efficiency of solar installations. These systems find application in various settings, ranging from residential rooftops to expansive utility solar farms. A major benefit of bifacial PV systems lies in their capacity to collect more sunlight compared to conventional mono-facial systems. This advantage stems from their ability to utilize albedo, the reflection of sunlight off nearby surfaces such as the ground, rooftops, or other reflective materials. Presently, bifacial solar cells exhibit impressive performance, with the capability to produce up to 30% more energy than mono facial systems under optimal conditions. This increased energy generation is primarily attributed to the additional sunlight absorbed by the rear side of the panel, which remains untapped in traditional systems. Bifacial PV systems prove especially efficient in locations with significant reflected sunlight, including snowy regions and deserts with highly reflective surfaces.

In terms of efficiency, modern bifacial solar cells have reached conversion efficiencies exceeding 20%, with some of the latest commercial models achieving even higher values. These developments are primarily due to advancements in materials, cell architectures, and manufacturing processes.

For example, bifacial systems utilizing Passivated Emitter and Rear Contact (PERC) technology and HETERO JUNCTIO n solar cells (HJT) have greatly enhanced both efficiency and longevity. Additionally, bifacial solar panels are

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increasingly integrated with tracking systems, enabling them to adjust their position and follow the sun's trajectory throughout the day. By incorporating solar trackers, bifacial systems can optimize energy collection from both sides of the panels, further enhancing their performance. In large-scale installations, bifacial systems combined with tracking technology have proven to be highly efficient, with some projects reporting energy generation improvements of over 35%. The ongoing efforts to reduce the cost of bifacial modules have also contributed to their rising popularity. While bifacial systems have historically been more expensive to manufacture due to their complex design and the need for specialized materials, the cost gap between bifacial and monofacial systems has narrowed significantly. With the growing global demand for solar energy and the impact of economies of scale, the cost of bifacial solar panels is anticipated to become increasingly competitive compared to conventional systems.

This paper explores the application of Maximum Power Point Tracking (MPPT) control techniques that optimize the power output of bifacial solar panel. Bifacial solar panels have gained popularity due to their ability to generate electricity from both sides of the panel, increasing their overall efficiency. However, optimizing the power output of bifacial solar panels can be challenging, as the maximum power point can shift depending on the amount of light that hits the front and back of the panel. The global shift towards sustainable energy sources has led to a surge in the adoption of solar power systems. Among the various types of photovoltaic panels, bifacial solar panels have emerged as an attractive option due to their ability to harvest energy from both sides.

II. LITERATURE REVIEW

A detailed literature survey has been carried out in the area of solar PV System & incremental conductance MPPT algorithm.

Some of the works that were carried out by MPPT Charge control in Bifacial solar panels Using Different algorithm techniques. In [1] compares the different technique for MPPT in PV system. MPPT algorithms such as (P&O) conductance and Incremental Conductance and tells about the efficiency of both and which is better.

They execute using SIMULINK/MATLAB Software. [2], unlike the mono facial PV Array module that generates Power by only one side of the Panel, but in the case of bifacial PV module it generates power from front and rear side of the panel. Here they were verifying the power generation loss due to shading area and comparing to the mono facial solar panel to confirm that bifacial solar panel is more effective. [3], the comparative simulation study of two widely used MPPT algorithms.

Comparing the various output for power, voltage and current for each different condition was concluded. [4], evaluation and simulation for MPPT algorithm i.e. (P&O) was to track maximum power point in MATLAB, and found the maximum power under any atmospheric conditions.[5], to increase the DC voltage, they use DC-DC Convertor. For the maximum output power, it can be found by using INC conductance.

The output power was used to drive a DC-DC converter, reducing system complexity.[6], reviewing the shading and non-shading portions in PV system using MPPT Algorithm.[7][8][9], evaluating and reviewing the various algorithms of MPPT Control technique in PV system.[10], performance of bifacial panel was evaluated in simulation.[11],

Comparing the MPPT charge controller with PWM charge controller. [12], controlling techniques for solar PV system.[13], hybrid boost convertors used in PV system.[14], performance of various convertors fed inverters in PV.[15], using the MPPT charge controller for PV system in low power applications.

As a result, bifacial solar PV technology is becoming increasingly popular and gaining market share, providing a promising alternative to Ahmed *et al.* (2020) provided a comprehensive review of bifacial PV technologies, discussing their evolution, efficiency, and market potential.

The paper emphasized the technological advancements in bifacial modules, including their ability to harness energy from reflected sunlight, which improves overall energy conversion efficiency. Goswami & Sadhu (2021) investigated floating solar PV systems integrated with wastewater management. The study demonstrated how these systems can generate clean energy while simultaneously conserving water resources. The research underscored the economic and environmental benefits of combining energy generation with water management practices. Arnaoutakis *et al.* (2022) explored single-crystal monolithic upconverter solar cells with integrated optics, aiming to overcome efficiency barriers in solar energy

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conversion. The innovative tandem device architecture showed promising improvements in photon utilization, advancing the development of high-efficiency solar technologies.

Atalay & Cankurtaran (2021) analyzed a large-scale solar dryer integrated with Phase-Change Material (PCM) energy storage. The energy, exergy, and exergo economic evaluations revealed that PCM-enhanced solar dryers are more efficient and environmentally friendly. The research provided insights into optimizing energy use in agricultural drying processes.

Attia *et al.* (2024) examined the influence of nanofluids and glass cooling on the performance of hemispherical solar stills. Their findings indicated that combining nanofluids with an innovative cooling mechanism significantly increased energy and exergy efficiencies. This experimental work highlighted cost-effective strategies for improving water desalination. In another study, Attia *et al.* (2024) explored the use of copper oxide micro- and nanoparticles to enhance hemispherical solar stills. Their research demonstrated that incorporating these particles improved yield and overall performance. The cost-benefit analysis supported the practicality of this approach in water-scarce regions.

Aydın *et al.* (2022) investigated a PV/T hybrid system integrated with an inner plate-finned cooling mechanism using Al2O3 nanofluids. Results showed significant improvements in both electrical and thermal outputs, demonstrating the potential of nanofluid cooling systems to optimize hybrid PV/T performance.

In a follow-up study, Aydın *et al.* (2024) expanded their analysis of PV/T hybrid systems using alternative nanofluids and novel cooling designs. The research reinforced earlier findings, showcasing how innovative cooling techniques and material enhancements can further improve energy efficiency and reliability in hybrid solar systems. Baghizade *et al.* (2024) conducted a comprehensive laboratory and mathematical analysis to understand salt deposition in closed solar desalination ponds. Their investigation revealed that the salt deposition process is influenced by solar radiation, temperature gradients, and evaporation rates. The mathematical model developed was validated against experimental data, providing a reliable tool for predicting salt accumulation and its impact on system efficiency.

III. PROPOSED METHODOLOGY

This study was conducted using a model-based simulation approach with MATLAB Simulink. The research stages were systematically designed to evaluate and compare the performance of the P&O and INC MPPT algorithms on a 315 Wp PV system connected to a boost converter. The research stages include modeling the PV system and boost converter, implementing the P&O and INC MPPT algorithms, analyzing performance based on quantitative parameters, comparing results, and evaluating performance.

A. System Modeling

The initial stage of the research was to build a 315 Wp PV system model based on datasheet parameters under standard conditions (1000 W/m² irradiance and 25°C temperature) and dynamic conditions. The dynamic conditions are solar radiation and temperature data taken every hour from 07:00 to 17:00. The PV module was connected to a DC–DC boost converter that functions as an operating point regulator through duty cycle control. The system model was developed in MATLAB/Simulink to ensure flexibility in testing various control algorithms and environmental condition scenarios.

B. Implementation of MPPT Algorithms

In this stage, two MPPT algorithms were separately implemented in the same system to ensure that the test conditions were identical. The P&O method works by applying a small perturbation to the duty cycle and iteratively evaluating the change in PV output power until it reaches a condition close to the maximum power point. The INC method determines the position relative to the maximum power point based on discrete changes in current and voltage. The duty cycle is then adjusted until the optimal conditions are achieved. Both algorithms use the same duty cycle limits to maintain objectivity in the comparison. The system was initialized from a duty cycle of 0 ($D = 0$) and allowed to converge toward the optimal point to evaluate the full tracking capability. The initial reference point of 20% mentioned in Fig. 3 was used only as a benchmark to verify the MPP location before the automated algorithms were executed.

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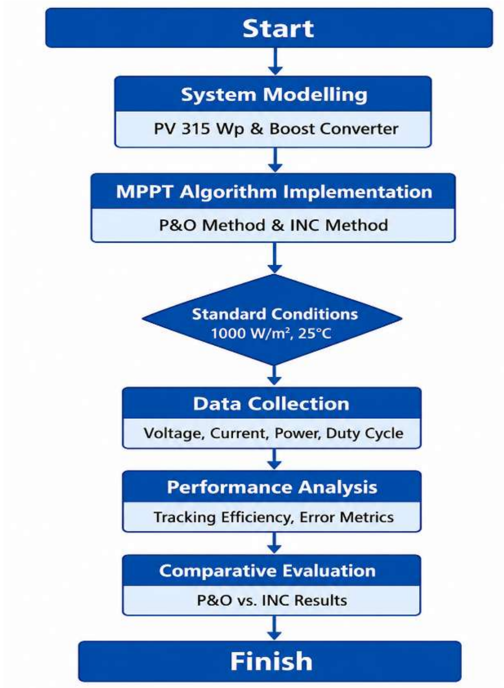

Fig. 1. Research Methodology

C. Simulation Testing

The tests were conducted under both the standard and dynamic conditions. These conditions were used to analyze the steady-state characteristics and tracking accuracy. The scenarios were run for the same simulation duration to ensure the consistency of the results.

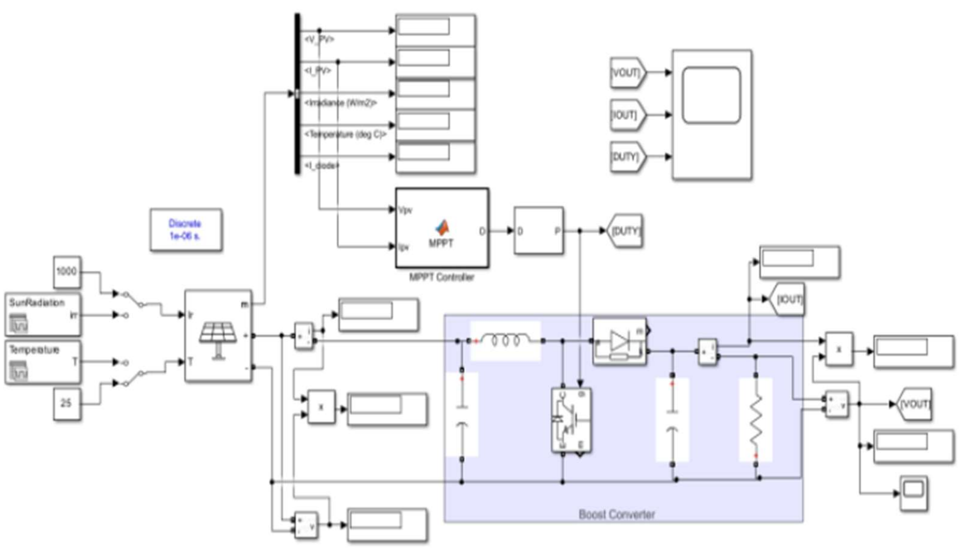

Fig. 2. MPPT system on PV using MATLAB Simulink

Fig. 2 shows the MPPT system on PV using MATLAB Simulink. Solar radiation and temperature inputs under the standard and dynamic conditions. Under standard conditions, the temperature is 25°C, and the solar radiation is 1000 W/m. The dynamic conditions are the results of temperature and solar radiation measurements taken between 07:00 and 17:00. The PV output is connected to the MPPT and boost converter.

D. Data Acquisition and Performance Evaluation

The PV output voltage and current, PV output power, duty cycle value, and converter voltage response over time were recorded during the simulation. This data is used to analyze how the MPPT algorithm regulates the system's operating point to achieve maximum power. The tracking efficiency, absolute power error, MAPE, rise time, settling time, maximum overshoot, and steady-state error were used for performance evaluation. Time-domain analysis was used to assess the accuracy, stability, and convergence characteristics of the P&O and INC methods in tracking the maximum power point.

E. Comparative Analysis Procedure

The P&O and INC methods were compared using MATLAB simulations. The comparison was conducted without changing the system configuration to maintain identical test conditions. The evaluation of both methods was based on quantitative metrics, such as steady-state stability and dynamic response, presented through graphs of voltage and power responses versus time and parameter comparison tables to ensure objective analysis.

IV. RESULTS AND DISCUSSION

Both MPPT algorithms were implemented in identical system configurations, including the same PV model, boost converter parameters, duty cycle limits, and initial conditions, to ensure a fair and unbiased comparison. This approach eliminates external influences, such as converter design differences or parameter tuning variations, commonly found in previous studies. Therefore, the observed performance differences can be directly attributed to each algorithm's intrinsic characteristics, strengthening the validity and reliability of the comparative analysis.

Duty Cycle Characteristics

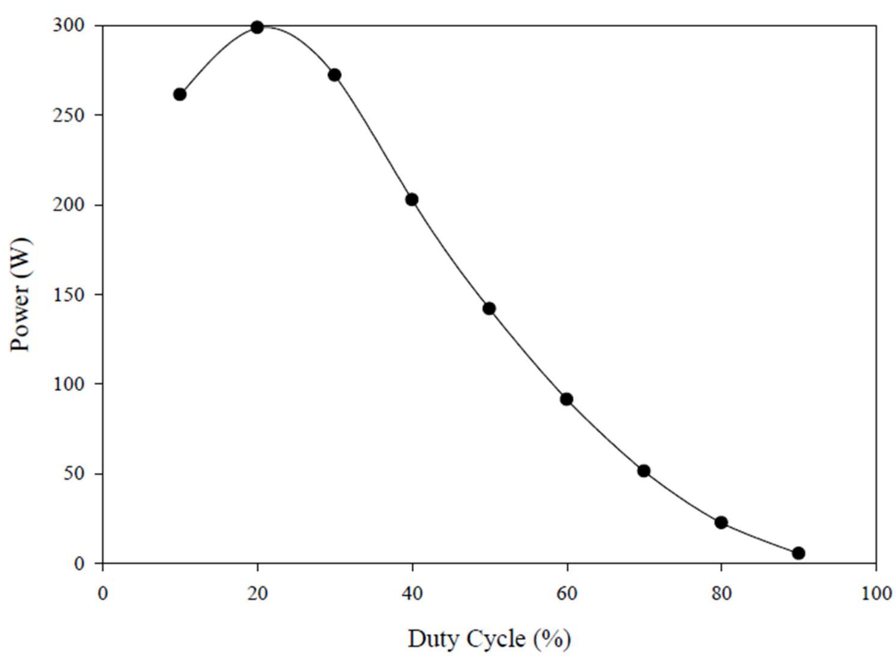

Fig. 3. Comparison of The Duty Cycle and Power Output of The Boost Converter

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Fig. 3 compares the duty cycle and power output of the boost converter. The reference maximum power (PMPP, ref) is defined as the theoretical peak power of 315 Wp obtained from the STC datasheet of the PV module. The 300 W observed in the initial duty cycle (Fig. 3) represents the converter's achievable maximum power after accounting for inherent system losses. Based on Eq. (9), the tracking efficiency is calculated as follows:

$$\eta_{tracking} = \frac{300}{315} \times 100 = 95.2\%$$

The tracking efficiency value of 95.2% indicates that the duty cycle-based MPPT system can extract near-maximum power under standard conditions. The difference of approximately 5% is due to duty cycle resolution limitations, boost converter losses, and operating point deviation from VMP. These results indicate that the proposed system has stable and reliable performance. The initial reference point of 20% is only used as a benchmark to verify the MPP location before running the automatic P&O and INC algorithms.

Fig. 4 shows the relationship between the duty cycle and output voltage and current of a PV system connected to a boost converter under standard conditions. When the duty cycle is increased from 10% to 90%, the PV voltage and current also gradually decrease. This condition indicates that increasing the duty cycle shifts the PV module's operating point away from the VMP, so that the system no longer operates at the maximum power point. Therefore, selecting the right duty cycle is crucial to keeping the system operating around the MPP and maintaining optimal output power.

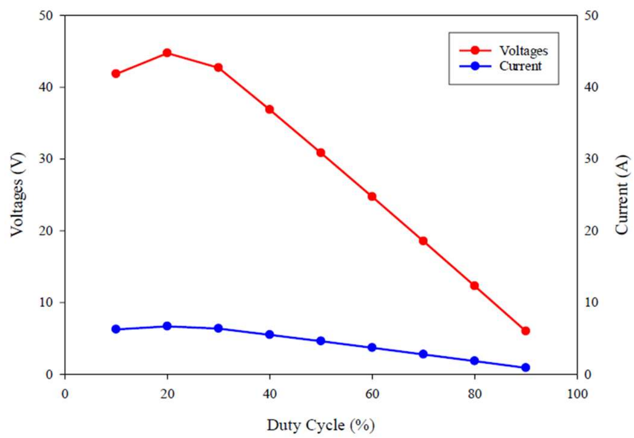

Fig. 4. Comparison of Duty Cycle with Boost Converter Output Voltageand Current

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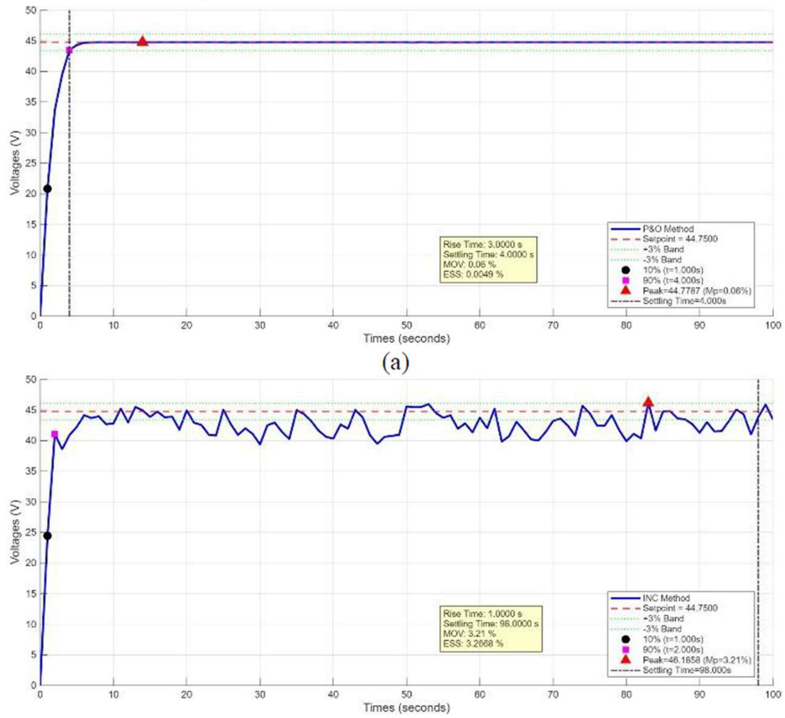
B. Comparison of P&O and INC Performances with Constant Input



(a) (b)

Fig. 5. Comparison of The Voltage Response Using The (a) P&O and (b) INC Methods with Constant Input

Fig. 5 compares the voltage responses obtained using the P&O and INC methods. At the beginning of time (t ≈ 0 s), the voltage rapidly increases until it approaches the set point value, indicating a convergence process toward the maximum operating point. The INC method in Fig. 5 (b) experiences significant oscillations around the reference point after reaching a condition close to the set point, whereas the P&O method in Fig. 5 (a) shows a more stable response with smaller fluctuations. This indicates that the P&O method has a more stable tracking capability than the INC method in maintaining the voltage around the MPP point. Both methods can reach the reference point. The P&O method provides better steady-state performance with a lower voltage ripple under standard/constant conditions.

TABLE I. RESPONSE OF THE OUTPUT VOLTAGE OF THE CONVERTER USING THE P&O AND INC METHODS

Dynamic Response	P&O Method	INC Method
Rise Time (s)	3	1
Settling Time (s)	4	98
Maximum Overshoot/MOV (%)	0.06	3.21
Error Steady State/ESS (%)	0.0049	3.2668

Fig. 6 compares the output power obtained using the P&O and INC methods. At the beginning of time, the power rapidly increases from a low condition to near the set point value, indicating a convergence process toward the MPP point. The INC method (blue line) experiences large power fluctuations around the maximum point after a condition near the set point is reached. In contrast, the P&O method (red line) shows a more stable response with much smaller oscillations around the reference value. This shows that the P&O method has better steady-state performance in maintaining maximum power under standard/constant conditions.

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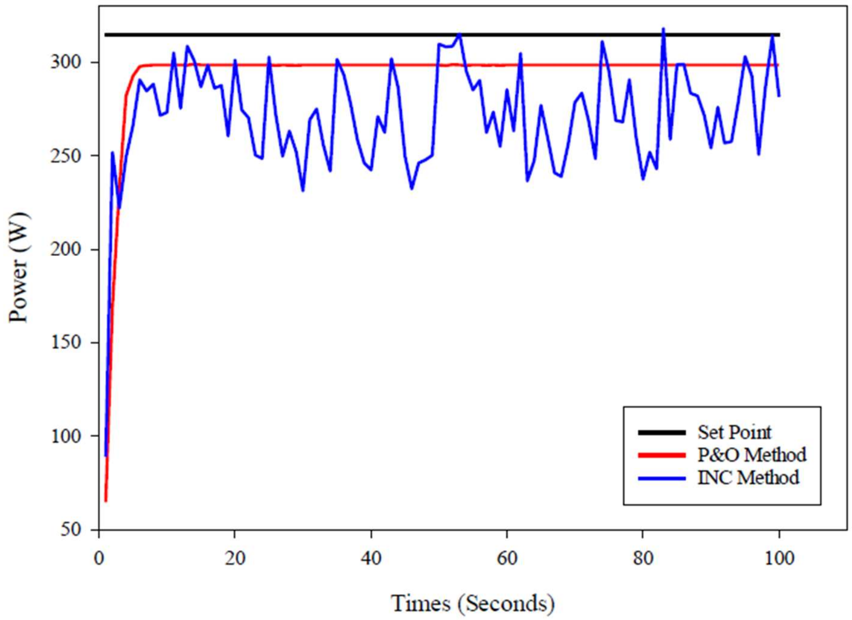

Fig. 6. Comparison of The Power Response Using The P&O and INC Methods with Constant Input

The P&O method has better tracking accuracy and stability than the INC method with a rise time of 3 s, settling time of 4 s, MOV of 0.06%, and ESS of 0.0049%, especially in maintaining steady-state conditions around the MPP. The absolute power error value in the P&O control method is 20.85 W, whereas that in the INC method is 43.85 W. Additionally, the MAPE value for power shows that the P&O method produces an error of 6.6%, whereas the INC method produces an error of 13.9%. This indicates that the P&O method has a smaller absolute power error and MAPE value than the INC method in the standard condition/constant.

C. Comparison of P&O and INC Performances with Dynamic Input

The P&O and INC methods were compared using dynamic input conditions. Two input parameters, solar radiation and temperature, were measured hourly from 7:00 to 17:00. Under dynamic conditions, the MAPE value obtained from the INC method was 20.87%, whereas that of the P&O method was 37.26%.

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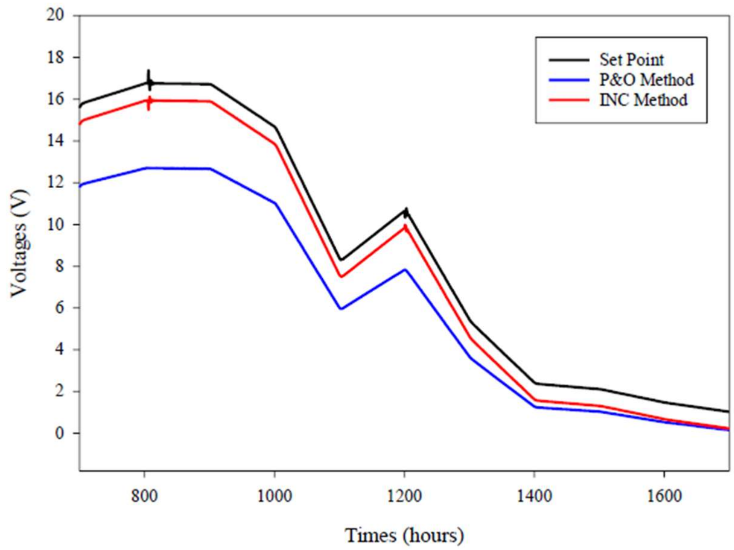

Fig. 7. Comparison of The Voltage Response Using The P&O and INC Methods with Dynamic Input

The INC method is superior under dynamic conditions because it can more accurately respond to environmental changes through conductance comparison, thus increasing efficiency. The P&O method is more stable and has a smaller error under constant conditions. Computationally, P&O is simpler and lighter, making it suitable for systems with limited resources, whereas INC is more complex but provides better accuracy under changing conditions. Therefore, a trade-off exists between computational complexity and tracking performance when selecting an MPPT method.

V. CONCLUSION

This study presents a comparative analysis of the P&O and INC MPPT methods based on duty cycle regulation in PV systems. The results show that both methods can track the maximum power point under both constant and dynamic irradiance and temperature conditions. The P&O method produces an absolute power error of 20.85 W with an MAPE of 6.6% under constant conditions, whereas the INC method produces an absolute power error of 43.85 W and a MAPE of 13.9%. Meanwhile, under dynamic conditions, the MAPE value using the P&O method is 37.26% and that using the INC method is 20.87%. Under constant conditions, the P&O method outperforms the INC method because it is more stable and has smaller errors than the INC method. It is superior under dynamic conditions because it is more responsive to environmental changes. This study is expected to provide a structured and implementable evaluation framework for PV MPPT systems under real conditions.

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