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Modeling and Performance Analysis of a P&O-Based MPPT Controller for PV Systems under Varying Environmental Conditions

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Abstract. To raise photovoltaic conversion efficiency, this paper revisits the perturb-and-observe (P&O) method for maximum-power-point tracking (MPPT). As a classic and widely adopted technique, the P&O algorithm offers a straightforward yet effective approach to maximizing power harvest from PV systems. Once the P&O control law is derived, a complete MATLAB/Simulink model of a PV array with integrated P&O-based MPPT is assembled. This modeling process allows for a detailed examination of system dynamics under controlled conditions. Simulations under varying irradiance and temperature confirm the model, validating its behaviour across the operating range. Such tests are essential, as real-world solar installations frequently experience fluctuating weather. The controller reaches the maximum power point quickly and accurately, exhibiting steady-state stability and rapid dynamic recovery after environmental changes, which increases energy yield and system reliability. This robust performance ensures consistent operation despite external disturbances. The results highlight the practical merit of the P&O algorithm and provide a theoretical basis for optimising real-world PV installations. In conclusion, the study successfully demonstrates the continued relevance and effectiveness of the P&O method for enhancing solar energy utilization.

Keywords: Photovoltaic Power Generation, Perturbation Observation Method, Maximum Power Point Tracking

1. Introduction

Global pressure for cleaner energy is propelling solar PV and other renewables into power networks at a pace never seen before. Mounting concerns over energy security and pollution keep renewables on an upward trajectory. Among them, photovoltaic generation stands out: its fuel is inexhaustible, its emissions are zero, and its modules can be deployed almost anywhere, making it a pillar of the 'dual carbon' strategy. Yet the current–voltage profile of a PV cell is markedly non-linear and weather-dependent. Irradiance and temperature shift the curve, so a single maximum-power point (MPP) exists only momentarily [1]. Maximum power point tracking (MPPT) is therefore indispensable. By locking the operating point to the moving MPP, the controller secures the highest

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possible energy yield and defines the performance ceiling of any PV installation—an objective that continues to dominate research efforts.

Researchers around the world have put forward a wide range of MPPT algorithms. Classical techniques—most notably Perturb and Observe (P&O) and Incremental Conductance (INC)—usually force designers to accept a compromise between tracking speed and steady-state ripple. Their effectiveness also drops markedly once the array is partially shaded [2]. Among these traditional options, P&O still dominates because its structure is simple and easy to code. Yet it continues to oscillate around the maximum power point in steady state and can mis-track when irradiance shifts quickly, trapping the system in a local peak [3]. INC identifies the MPP by checking whether the incremental conductance equals the instantaneous conductance. In principle this allows ripple-free operation and a faster, more accurate reaction to environmental drift. The downside is higher implementation overhead and the classic fixed-step conflict between speed and precision [4]. Recently, a wave of refined intelligent algorithms has been introduced to push MPPT performance further. Xiao Y et al., for example, combined a Long Short-Term Memory network with an improved walking optimisation to raise PV efficiency under irregular irradiance [5, 6]. Such approaches demand large training sets and heavy computation, so they are hard to deploy on low-cost controllers. Hence a pressing, yet difficult, goal is to re-engineer the P&O method so that its transient response and steady-state behaviour are balanced, a step that would markedly extend its use in high-performance photovoltaic systems.

Against this backdrop, the paper models a P&O-based MPPT system for photovoltaic arrays. By tightening the theoretical account of the P&O algorithm and embedding it in a full system model, the study seeks a measurable gain in overall performance. Chapter 2 revisits the foundations of maximum-power-point tracking and unpacks the P&O method, spelling out its governing equations and control logic. Chapter 3 assembles a complete model of the PV cell and its P&O-based MPPT controller in MATLAB/Simulink. Simulations under varying irradiance and temperature are run to benchmark the algorithm and to demonstrate its merits. Chapter 4 closes the study by summarising the key findings and pointing to the refinements and application avenues that remain open.

This study sets out a concise modelling and simulation framework for analysing the P&O method in theory and in practice, giving designers a solid basis for building efficient, dependable photovoltaic systems.

2. Fundamentals of MPPT and perturbation & observation algorithm

2.1. Fundamentals of MPPT

Photovoltaic arrays are run continuously at their peak-power point so that no available solar energy is left unused, a practice that markedly raises the overall conversion efficiency. Unlike batteries, modules cannot deliver a steady voltage or current; their output is governed by ambient conditions, above all irradiance and cell temperature. A clear midday can yield several times the power of heavy cloud, while rising temperature depresses the terminal voltage. For any given irradiance–temperature pair the panel presents a single optimum, the maximum-power point, whose coordinates are designated Vmp for voltage and Imp for current [7]. This operating point is held by an MPPT controller.

Maximum-power-point tracking is the backbone of every photovoltaic plant: its only job is to extract the highest wattage the modules can deliver at any instant. An intelligent controller—typically a DC-DC converter governed by a dedicated algorithm—serves as the scheme's brain. It continuously monitors array voltage and current, nudging the operating point so their product

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remains at the maximum permitted by the prevailing irradiance. Rapid measure-compare-adjust cycles lock the array onto the V-I coordinate that yields peak power; once there, the circuit keeps the panel at that sweet spot while the downstream stage reshapes the power to match the exact voltage and current required by the battery or grid. Because the array is no longer pulled away from its optimum, the plant usually harvests 10–30 % more energy than it would under conventional control [8].

MPPT is necessitated by the dynamic and variable output characteristics of solar panels. It addresses this challenge by providing an effective solution to dynamically maintain operation at peak efficiency.

2.2. Principle and analysis of the perturb & observe algorithm

Among MPPT techniques, the perturb-and-observe (P&O) algorithm is still the most widely used and time-tested. It works as a repeating cycle: perturb, observe, decide [9]. In the perturbation step, the controller nudges the array voltage up or down by adjusting the converter duty cycle. The output power is then sampled and compared with the previous reading to see which way it has moved. If power has increased, the controller keeps the same adjustment direction; if it has dropped, the next step reverses course. Repeating this sequence holds the operating point near the maximum power point. Figure 1 illustrates the P-V characteristic curves of a PV panel under different irradiance levels, highlighting the marked MPP where each curve exhibits a distinct peak [10].

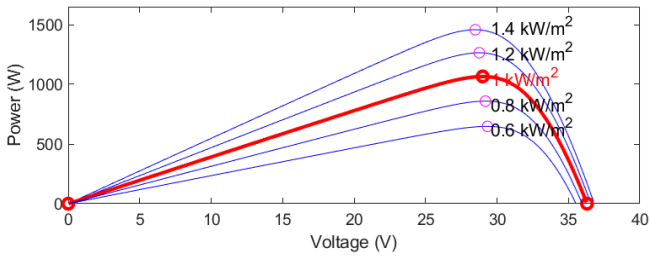


Figure 1. Photovoltaic panel P-V characteristic curve

On the left side of the MPP, the power increases as the voltage rises. Then the slope should be greater than 0, that is, $dP/dV > 0$ On the right side of the MPP, power decreases as the voltage increases. Then the slope should be less than 0, that is, $dP/dV < 0$. At the MPP, it reaches the maximum power. At this point, the slope is exactly 0, that is, $dP/dV = 0$.

All the decision-making logic of the disturbance observation method is based on the judgment of the dP (power change amount) and dV (voltage change amount) symbols. Therefore, for different slope situations, the following different decisions can be made.

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Table 1. The slope of the power curve and the corresponding decision

Power curve slope	Operating Point Location	Decision
$dP/dV = 0$	At MPP	Maintain Current Action
$dP/dV > 0$	Left of MPP	Boost the Action
$dP/dV < 0$	Right of MPP	Reduce the Action

Based on the above mathematical derivation, the following judgment criteria can be obtained. By measuring the current voltage $V(k)$ and current $I(k)$, multiply them to obtain power $P(k)$. Compare $P(k)$, $V(k)$ with the values of the previous cycle $P(k-1)$, $V(k-1)$, calculate $dP = P(k) - P(k-1)$ and $dV = V(k) - V(k-1)$, and then based on the above relationship, determine how to adjust the working voltage. However, in practice, it is usually to change the duty cycle D of the DC-DC converter, gradually approaching the maximum power point.

Figure 2 shows a circuit diagram of a photovoltaic panel connected to a boost circuit. It can be seen that the output voltage and current of the photovoltaic panel are equal to the input voltage and current of the boost. The following concepts are defined: the output voltage V_{pv} and output current I_{pv} of the photovoltaic panel, the output voltage V_{ob} and output current I_{ob} of the boost, the load resistance R, and the duty cycle D.

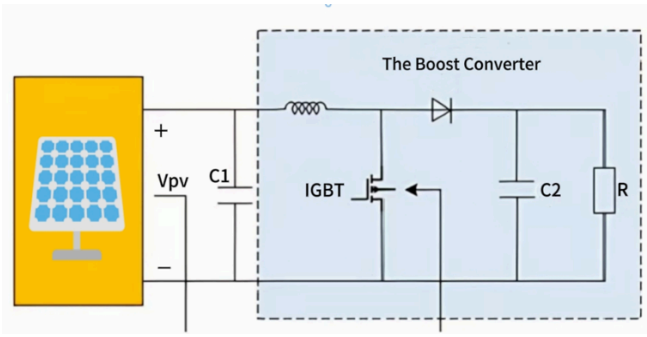


Figure 2. Circuit diagram of the photovoltaic panel connected to the boost circuit

Based on the characteristics of the boost circuit, the following relationship is obtained:

$$\{ V_{pv} = (1-D)V_{ob}, V_{pv}I_{pv} = V_{ob}I_{ob}, I_{ob} = (1-D)I_{pv}, R = V_{ob}/I_{ob} \} \tag{1}$$

From the above (1), it can obtain

$$V_{pv}/I_{pv} = (1-D)^2 R \tag{2}$$

When the work is stable, the current is constant, that is, I_{pv} is constant. According to equation (1), the voltage is negatively correlated with the duty cycle. Therefore, increasing the voltage will

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reduce the duty cycle; decreasing the voltage will increase the duty cycle [11,12].

3. Simulink system modeling and analysis

3.1. System main architecture

Based on the above principle, the simulation model shown in Figure 3 was built in Simulink. It includes photovoltaic cell units, power measurement units, and MPPT control units.

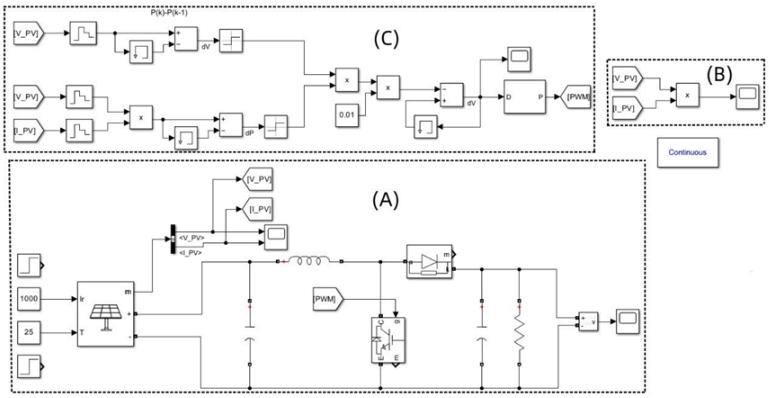


Figure 3. System architecture diagram

Figure 3(A) illustrates the photovoltaic cell unit. On its left, two constant modules fix the light intensity and temperature, while two step modules impose step changes on the same variables. The array itself is built from the PV Array block: five panels in parallel, one in series, each rated at 213.15 W. The m-port of the array feeds a Bus Selector that extracts V_PV and I_PV; these signals drive two go-to blocks. An oscilloscope simultaneously captures the evolving voltage and current waveforms. The array output is delivered to a boost converter. Component values are C1 = 1F at the input, L = 10mH, C2 = 10mF at the output, and R = 1Ω for the load. A voltmeter and a second oscilloscope on the right allow quick verification and tuning of the converter parameters [13].

The power measurement unit is illustrated in Figure 3(B). V_PV and I_PV are multiplied in the Product module to yield the instantaneous power, which is then fed to the oscilloscope to display the power waveform.

The MPPT control unit is shown in Figure 3(C). V_PV and I_PV are sampled every 0.01 s by a Zero-Order Hold block. After sampling, the Memory and Add blocks derive dV from successive V_PV values; the Product block forms instantaneous power P from V_PV and I_PV, and a second Memory–Add pair yields dP. Because only the sign of the product $dP \bullet dV$ matters, a Sign block followed by a Product block returns +1 or −1. This sign is multiplied by a fixed step of 0.01 to produce the duty-cycle adjustment. The updated duty cycle is accumulated with another Add–Memory pair, fed to a PWM Generator to create the switching signal, and routed to an oscilloscope to display the duty-cycle transient.

3.2. Maximum power point tracking under specific conditions

The simulation was conducted under specific conditions of 1kW/m² light intensity and 25 ℃ temperature [14]. The simulation duration was 1 second. As shown in Figure 4, both the light intensity and temperature of the photovoltaic panel were input as constants. Figure 5 shows the

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maximum power point of the photovoltaic panel under the aforementioned conditions, which is (29V, 1065.75W).

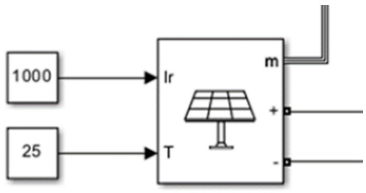


Figure 4. Input of photovoltaic cells under specific conditions

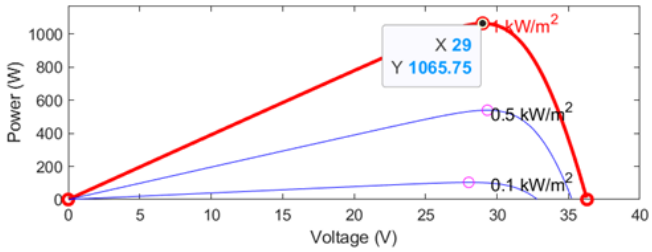


Figure 5. Maximum power point under the conditions of a temperature of 25℃ and a light intensity of 1kW/m²

System simulation produced the output voltage and current traces shown in Figure 6(a) and the power trace in Figure 6(b). During start-up (0–0.1 s) the system undergoes a pronounced transient: both power and voltage swing away from their initial levels and then settle. Voltage converges to roughly 29V, the maximum-power-point value, confirming that the P&O-based MPPT reacts promptly and parks the operating point close to the peak. After 0.1 s the system enters steady state: power hovers near 1060W, only 5.75W below the theoretical maximum of 1065.75W, while voltage locks at 29V, matching the theoretical MPP voltage. These figures verify accurate steady-state tracking. Under the test conditions—irradiance 1kW/m⁻², temperature 25°C—the simulated values align closely with theory, validating the model and the ability of the P&O algorithm to track the photovoltaic maximum power point.

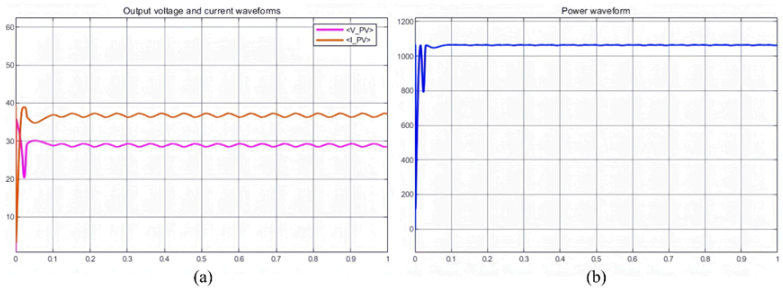


Figure 6. Waveforms of voltage, current and power under specific conditions

3.3. Maximum power point tracking under sudden changes in light intensity

The simulation was conducted under the conditions of a temperature of 25℃ and a light intensity that changed from 1kW/m² to 2kW/m². The simulation duration was 2 seconds, and the time for the light intensity to change was 1.5 seconds. As shown in Figure 7, the temperature of the photovoltaic panel was input as a constant value, and the light intensity was input as a step function. Figure 8

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shows the maximum power points of the photovoltaic panels under the conditions where the temperature is 25°C and the light intensities are 1kW/m² and 2kW/m² respectively, which are (29V, 1065.75W) and (27.4836V, 1995.16W).

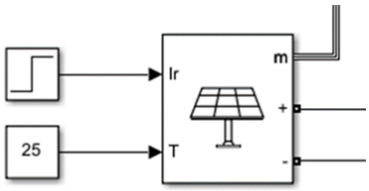


Figure 7. Input of photovoltaic cells under sudden change of light intensity

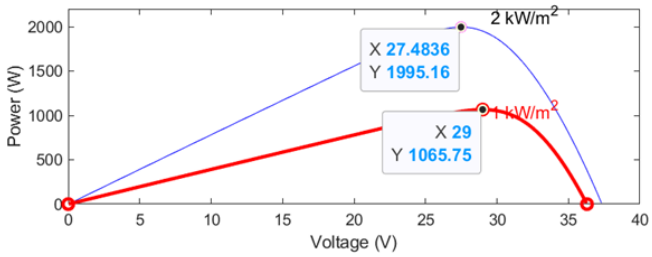


Figure 8. Maximum power point under the conditions of a temperature of 25°C and light intensities of 1kW/m² and 2kW/m²

Through system simulation, the output voltage and current waveforms in Figure 9(a) and the power waveform in Figure 9(b) were obtained. The startup stage is consistent with the maximum power point tracking under specific conditions. When t = 1 second, the illumination intensity suddenly increased from 1kW/m² to 2kW/m², and the system quickly entered the transient adjustment process. The power rapidly increased from approximately 1060W to around 2000W, which was basically consistent with the theoretical maximum power of 1995.16W. Moreover, the overshoot was small and the adjustment time was short. The output voltage gradually approached the theoretical maximum power point voltage of 27.48V under the new operating conditions, and finally stabilized at around 27V, with the deviation remaining within a reasonable range. During this transient process, the system responded promptly, and all parameters were adjusted smoothly without any obvious oscillations. This indicates that the P&O method adopted still has good dynamic adaptability and tracking performance when there is a sudden change in light intensity. The comparison with the theoretical values shows that the simulation results of the system under the sudden change of light intensity (light intensity increased from 1kW/m² to 2kW/m², temperature at 25°C) are highly consistent with the theoretical expectations, indicating that the established model is correct and the P&O method can effectively achieve the maximum power point tracking of photovoltaic cells.

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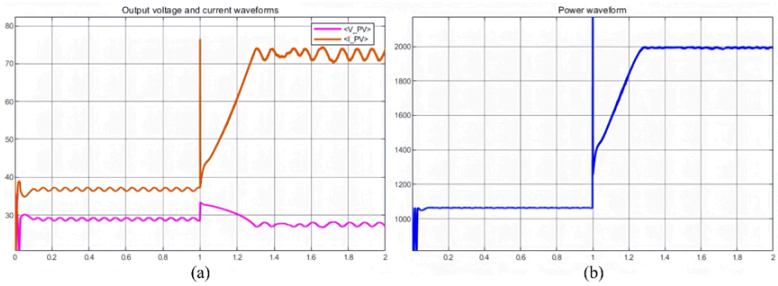


Figure 9. Waveforms of voltage, current and power under the condition of sudden change in light intensity

3.4. Maximum power point tracking under temperature variation conditions

The simulation was conducted under the conditions of a light intensity of 1kW/m² and a temperature change from 25 ℃ to 45 ℃. The simulation duration was 1 second, and the temperature change duration was 0.5 seconds. As shown in Figure 10, the light intensity of the photovoltaic panel was input as a constant value, and the temperature was input as a step function. Figure 11 shows the maximum power points of the photovoltaic panels under the conditions where the light intensity is 1kW/m² and the temperatures are 25 ℃ and 45 ℃ respectively, which are (29V, 1065.75W) and (26.3363V, 976.9W) respectively.

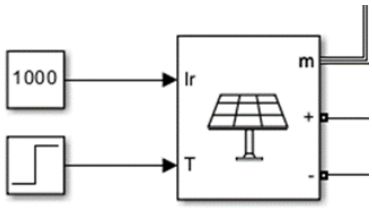


Figure 10. Input of photovoltaic panels under temperature change conditions

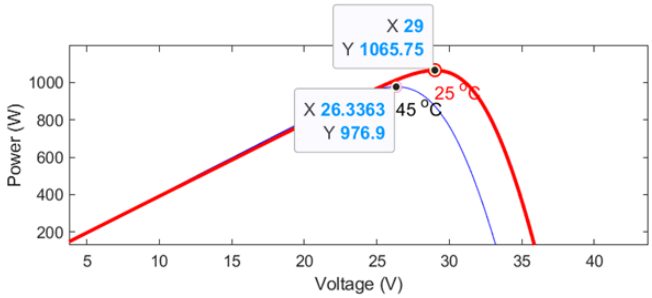


Figure 11. Maximum power point under conditions of 1kW/m² light intensity and temperatures of 25℃ and 45℃ respectively

Through system simulation, the output voltage and current waveforms in Figure 12(a) and the power waveform in Figure 12(b) were obtained. The startup stage is consistent with the maximum power point tracking under specific conditions. When t = 0.5s, the temperature suddenly increased by 25°C to 45°C, and the system quickly entered the transient adjustment process. The power rapidly decreased from approximately 1060W to around 970W, which was basically consistent with the theoretical maximum power of 976.9W. The overshoot was small and the adjustment time was

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short; the output voltage gradually approached the theoretical maximum power point voltage of 26.3363V under the new operating condition, and finally stabilized at around 27V, with the deviation within a reasonable range. Throughout the entire transient process, the system responded promptly, and all parameters were adjusted smoothly without any obvious oscillations. This indicates that the P&O method employed still possesses excellent dynamic adaptability and tracking performance when there is a sudden change in light intensity. The comparison with the theoretical values shows that the simulation results of the system under the sudden temperature change condition (light intensity of 1 kW/m², temperature increasing from 25°C to 45°C) are highly consistent with the theoretical expectations, indicating that the established model is correct and the P&O method can effectively achieve the maximum power point tracking of the photovoltaic cell.

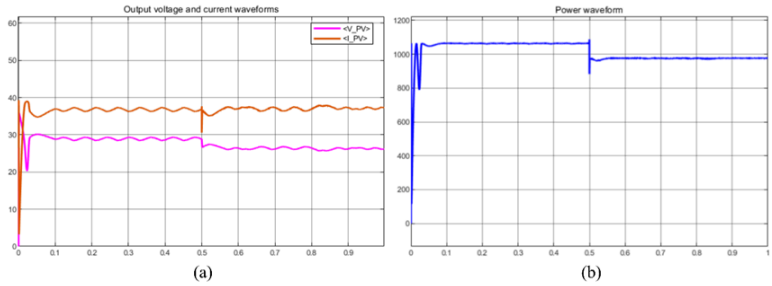


Figure 12. Waveforms of voltage, current and power under temperature change conditions

4. Conclusion

This study systematically models the perturb-and-observe (P&O) technique used for maximum-power-point tracking in photovoltaic systems and explores ways to improve its performance. By integrating theoretical analysis with a Simulink model, we first show why the standard P&O algorithm forces a trade-off between fast dynamic response and low steady-state oscillation. A full model of the PV module and its MPPT controller was built in MATLAB/Simulink; simulations under varying irradiance and temperature confirm that the P&O routine reliably locks onto the maximum power point, demonstrating both feasibility and robustness for field use. The same experiments highlight the drawbacks of a fixed perturbation step once the operating environment shifts.

The paper's main contribution is an open, reproducible modelling-and-simulation environment that exposes how the conventional P&O algorithm behaves and pinpoints its performance boundaries. These outcomes give engineers a clear set of rules for calibrating PV control loops and deliver both the theoretical footing and the practical steps to run efficient MPPT on inexpensive hardware. Although the study raises the baseline performance of the P&O method, its fixed step size still keeps speed and stability in tension. Adaptive stepping is therefore the evident next move: letting the increment contract or expand online should improve tracking velocity and accuracy. Hybrid approaches that merge P&O with intelligent techniques are also worth pursuing, yet they must be stressed under more erratic operating conditions to verify that the gains in precision and response carry a proportional rise in disturbance immunity, setting the stage for high-performance photovoltaic systems.

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