Three Fundamental MPPT Algorithms for Photovoltaic Applications

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Abstract. The effectiveness of photovoltaic systems is heavily influenced by the performance of Maximum Power Point Tracking (MPPT) techniques. This study provides a comprehensive analysis of existing MPPT approaches, detailing their fundamental mechanisms, advantages, drawbacks, and potential enhancement approaches. The primary objective is to offer readers a structured framework for comprehending three principal MPPT methodologies: Perturb and Observe (P&O), Incremental Conductance (INC), and Constant Voltage (CV) techniques. MPPT's central principle involves dynamically modifying PV module operating voltages to align system impedance with optimal values under varying environmental parameters like solar irradiation and thermal conditions. Such alignment enables sustained operation at peak power points, thereby improving energy conversion rates while reducing power dissipation. These operational advantages have stimulated substantial academic interest and research efforts in renewable energy optimization.

Keywords: Photovoltaic Power Generation; Maximum Power Point Tracking (MPPT); Energy Conversion Efficiency.

1 Introduction

The escalating global demand for renewable energy sources, coupled with heightened environmental awareness, has positioned solar energy as a predominant sustainable power solution. Photovoltaic cells exhibit nonlinear power output characteristics influenced by irradiance levels and thermal conditions. Operational parameters frequently deviate from optimal MPP conditions under practical scenarios, diminishing energy harvesting effectiveness. This technological challenge prompted the development of MPPT control strategies, now extensively implemented across photovoltaic systems [1]. The underlying mechanism exploits the distinctive unimodal current-voltage (I-V) characteristic curve of solar modules (illustrated in Figure 1), where singular peak power generation occurs. Through adaptive regulation algorithms, system operation can be dynamically maintained near this critical coordinate to maximize energy extraction efficiency.

Within the domain of maximum power point tracking techniques, perturb and observe (P&O), incremental conductance (INC), and constant voltage (CV) approaches have established themselves as foundational and widely adopted approaches due to

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their straightforward concepts and ease of execution [2][3]. Each technique presents distinct trade-offs regarding implementation expenses, noise resistance, and dynamic performance characteristics. Selection among these strategies should therefore be guided by specific application requirements and operational constraints. This comprehensive analysis examines the operational theories, comparative benefits, and inherent challenges associated with these conventional MPPT approaches, while also exploring potential enhancement opportunities. The review seeks to offer practical insights for both engineering professionals and scholarly investigators engaged in optimizing MPPT technology implementation and development.

2 MPPT Method

$$P = VI \tag{1}$$

Equation (1) demonstrates the foundational principles governing electrical power generation. The analysis reveals that voltage magnitude and current intensity serve as critical variables determining power output. Through strategic load management or deployment of power electronic conversion systems, operational parameters of photovoltaic arrays can be optimized to achieve peak performance efficiency. In solar energy conversion systems, incident radiation predominantly governs photocurrent generation, particularly observable in short-circuit current measurements, whereas thermal conditions primarily modulate open-circuit voltage characteristics [4]. This phenomenon occurs because photonic energy within electromagnetic radiation interacts with semiconductor materials - when photon energy surpasses the material's bandgap threshold, valence band electrons become excited into the conduction band, generating mobile charge carriers [5][6]. Consequently, enhanced irradiance levels produce proportionally greater current flow. Simultaneously, elevated temperatures intensify lattice vibrations, thereby raising intrinsic carrier concentrations. Given the inverse proportionality between carrier concentration and open-circuit voltage, this relationship directly impacts voltage characteristics.

The disparity between positive and negative charges diminishes, while the electrical potential gradient across the system simultaneously reduces. These combined influences result in fluctuating patterns of electrical current and voltage levels. Photovoltaic systems exhibit a distinctive unimodal profile on their power-voltage characteristics, demonstrating the existence of an optimal power generation point. Direct coupling of energy conversion components with storage batteries frequently results in suboptimal operation, often failing to approach peak efficiency thresholds and potentially functioning at diminished capacity [7,8]. Consequently, maximum power point tracking mechanisms become essential for maintaining operational parameters near optimal efficiency zones through continuous adjustment. Fundamentally, MPPT technology represents an adaptive impedance regulation system employing intelligent optimization algorithms, typically incorporated within photovoltaic charge regulation units or power conversion devices.

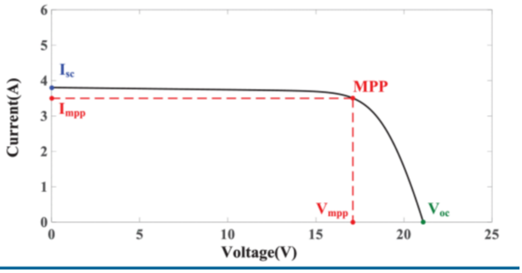

Fig. 1. I-V curve of the PV characteristics. (Note. Data from [9])

2.1 Perturb and Observe (P&O) method

The Perturb and Observe (P&O) technique represents a foundational maximum power point tracking approach. Its fundamental principle involves incrementally adjusting the voltage (ΔV) through iterative exploration until achieving optimal power output [10]. When the initial derivative reaches zero, the system identifies a potential extremum on the power-voltage characteristic curve. This unimodal curve features a singular peak where maximum power transfer occurs, specifically at the critical point where the second derivative becomes negative. Proximity to maximum power operation increases as the absolute value of the primary derivative approaches zero.

In operational scenarios where the power differential exceeds zero ($\Delta P/\Delta V > 0$), the system's working position resides leftward of the maximum power point, necessitating voltage elevation. Conversely, negative differential values indicate rightward positioning relative to the peak, requiring voltage reduction. Modern digital implementations typically approximate continuous derivatives through discrete measurements, calculating power variations (ΔP) relative to voltage changes (ΔV) between sampling intervals. This methodology enables precise tracking while accommodating real-time system dynamics.

In practice, the method usually does not calculate the derivatives directly. Because of its simplicity, the algorithm only perturbs the voltage and then compares the power before and after the change. If the power increases, the perturbation continues in the same direction. If the power decreases, the perturbation is reversed. This reduces the complexity of logic programming.

$$P_k = V_k \cdot I_k \tag{2}$$

The Mathematical Form. Let equation (2) equal to the instantaneous power at the sampling cycle, which is k, and $P(k-1)$ is the power in the previous cycle.

$$\Delta P = P_k - P_{k-1} \tag{3}$$

$$\Delta V = V_k - V_{k-1} \tag{4}$$

The change in power after disturbance is ΔP in formular (3), and the voltage change is ΔV in formular (4).

Decision Rule. If ΔP/ΔV>0, and the operating point is on the left side of the MPP, forward perturbation should continue formular (5).

$$V_{ref} = V_{ref} + \Delta V \tag{5}$$

If the operating point is on the right side of the MPP, reverse perturbation should be carried out formular (6).

$$V_{ref} = V_{ref} - |\Delta V| \tag{6}$$

Because irradiance and other environmental factors keep changing, the photocurrent is also changing. Therefore, the algorithm must keep perturbing to find the new maximum power point.

Despite its simplicity, the P&O method suffers from two significant limitations. The primary issue involves continuous oscillations around the MPP during stable operation. This persistent fluctuation occurs due to continuous adjustments made by the algorithm to follow the maximum power point, resulting in suboptimal energy harvesting. Research indicates this power losses correlate directly with perturbation magnitude - smaller step sizes diminish energy waste but prolong system response during environmental variations, creating an inherent performance compromise. Furthermore, the technique demonstrates vulnerability to abrupt solar irradiance shifts. During rapid cloud movement, substantial power fluctuations often exceed those induced by voltage adjustments, causing the system to misinterpret external environmental changes as self-induced perturbations. Such confusion leads to incorrect tracking decisions that require multiple correction cycles to resolve, inevitably decreasing energy conversion efficiency despite eventual system recovery.

To address these challenges, scholars have developed various enhancements to existing methodologies. A notable advancement involves implementing an adaptive step size technique, where the adjustment magnitude correlates with the absolute derivative of power relative to voltage (|dP/dV|). This strategy employs substantial step increments when the system operates distant from the peak power point (MPP), capitalizing on steeper gradients to accelerate convergence. Conversely, diminished step adjustments are utilized near the MPP region to minimize output fluctuations while maintaining operational stability. The mathematical formulation governing this adaptive approach is detailed in equation (7), demonstrating a dynamic equilibrium between tracking velocity and steady-state precision.

$$\Delta D_{k+1} = N \cdot \frac{|P_k - P_{k-1}|}{|V_k - V_{k-1}|} \tag{7}$$

Parameter N serves as an adjustment coefficient for scaling purposes. To maintain system stability and prevent operational anomalies, establishing an upper limit for incremental adjustments becomes crucial. This approach successfully balances the trade-off between computational efficiency and precision. Absent such constraints, initial phase adjustments might exhibit excessive magnitudes, potentially inducing erratic fluctuations or surpassing the converter's designated operational parameters. Furthermore, oversized increments could traverse the complete operational spectrum, potentially triggering repetitive transitions between adjacent power minima. Such oscillatory behavior would compromise both system reliability and energy conversion effectiveness.

An alternative approach involves three-point weighted evaluation, which captures power measurements from the current operational interval and two preceding cycles. By applying weighted factors during the comparison process, this technique enhances differentiation between environmental fluctuations and genuine perturbation signals, thereby strengthening system reliability. Nevertheless, prolonged irradiance variations still require multiple operational cycles for adaptation, extending calibration durations.

A more straightforward technique employs disturbance suspension protocols. When detecting power variations (ΔP) exceeding a predetermined activation value without self-induced disturbance origins, the system initiates a temporary suspension across multiple cycles. Tracking recommences post-stabilization, demonstrating effectiveness for abrupt environmental shifts. This methodology however introduces temporal inefficiencies during inactive phases, with primary implementation challenges residing in optimal threshold determination.

As a fundamental approach in MPPT technology, the Perturb and Observe (P&O) method strikes an optimal balance between operational efficiency, implementation complexity, and economic feasibility. While possessing certain constraints, its enhanced variants continue to demonstrate viability for mainstream commercial implementations.

2.2 Incremental Conductance (INC) method

This advanced Maximum Power Point Tracking strategy employs precise mathematical relationships between photovoltaic array's immediate conductivity and its rate of change. In contrast to traditional P&O methodology, the INC algorithm precisely locates the Maximum Power Point (MPP) through continuous calculation of the ratio between instantaneous conductivity and its incremental variation. The technique effectively minimizes steady-state power fluctuations while maintaining robust tracking capabilities during abrupt solar irradiation variations [11].

This approach shares theoretical foundations with the Perturb and Observe technique, as both identify maximum power points through characteristic curve analysis. The critical distinction lies in mathematical treatment: while P&O monitors power fluctuations to estimate optimal conditions, the Incremental Conductance strategy directly computes the initial derivative of electrical parameters. The analytical process initiates from the fundamental power equation (1), where voltage differentiation under extremum conditions yields equation (8) through rigorous calculus operations. Subsequent algebraic rearrangement of these differential relationships produces the definitive MPP criterion expressed in equation (9) [12]. The equilibrium state characterized by dI/dV=−I/V indicates precise maximum power operation, thereby requiring voltage stabilization through control mechanisms.

$$\frac{dP}{dV} = \frac{d(V \cdot I)}{dV} = I + V \cdot \frac{dI}{dV} = 0 \tag{8}$$

$$\frac{dI}{dV} = -\frac{I}{V} \tag{9}$$

When the derivative dI/dV exceeds -I/V, the system's operational position resides on the left-hand portion of the maximum power point, necessitating an upward voltage adjustment. Conversely, when dI/dV falls below -I/V, the operating point shifts to the MPP's right side, requiring voltage reduction. In microprocessor-based implementations, the differential term is numerically estimated through ΔI/ΔV computation. This control methodology follows sequential processing stages: Initial data acquisition involves capturing instantaneous voltage V(k) and current I(k) measurements. Subsequent analysis compares these readings with prior sampling cycle values (V(k-1) and I(k-1)) through difference calculations as specified in equations (10) and (11).

$$\Delta V = V_k - V_{k-1} \tag{10}$$

$$\Delta I = I_k - I_{k-1} \tag{11}$$

The control algorithm executes decision-making based on differential analysis:

For zero ΔV conditions, the system evaluates ΔI status - maintaining current voltage when ΔI=0 indicates stable environmental conditions. Positive ΔI values signal increased irradiance, triggering voltage elevation commands. Negative ΔI readings correspond to diminished irradiation levels, initiating voltage reduction protocols.

When ΔV is non-zero, the adjustment strategy follows specific criteria based on the main condition: Should the ratio ΔI/ΔV match −I(k)/V(k) within permissible tolerance limits, maintain the current voltage level. If ΔI/ΔV exceeds −I(k)/V(k), implement voltage reduction through either raising the reference voltage（Vref）value or decreasing the duty cycle proportion. Conversely, when ΔI/ΔV measures below −I(k)/V(k), execute voltage elevation by either lowering the reference voltage（Vref）parameter or boosting the duty ratio percentage.

Relative to the Perturb and Observe method, the Incremental Conductance method provides the advantage of operating without steady-state oscillations [13]. As long as the condition dI / dV = −I / V is satisfied, the operating point remains unchanged. This directly solves the problem of dynamic oscillation, because the algorithm has the ability to stop perturbation. It can also calculate the MPP directly through mathematics without relying on the trend of variation. Therefore, when the irradiance changes rapidly and strongly, it can respond quickly and accurately. In this case, it does not make the directional misjudgment that may appear in the P&O method. Since its principle is based on mathematical calculation, its accuracy is very high. It is only limited by the precision of sensors and the computing accuracy of the processor. With current technology, both are already very advanced, and even low-cost processors can easily reach an acceptable level.

The INC technique simultaneously presents multiple operational challenges. Primarily, its implementation requires complex mathematical computations, comparative analyses, and logical evaluations rather than the basic comparative approach employed in P&O, thereby demanding more sophisticated processing capabilities that elevate system costs. Secondly, the algorithm's precision critically depends on measurement accuracy for both voltage and current parameters. As operational decisions derive directly from these measurements, sensor inaccuracies like noise interference, calibration offsets, and measurement delays inevitably compromise the reliability of ΔV and ΔI computations. Such discrepancies may result in erroneous MPP determinations, potentially causing temporary system deviation from optimal operating points that diminishes energy conversion efficiency while prolonging stabilization periods. Additional complexity arises in establishing appropriate tolerance thresholds, where engineers must achieve optimal equilibrium between detection sensitivity and noise resistance - a parameter optimization challenge requiring extensive empirical testing. Furthermore, the voltage increment magnitude selection mirrors the P&O method's inherent conflict between achieving rapid environmental adaptation and maintaining steady-state tracking precision.

To address these challenges, researchers have proposed several enhancements. First, the step size may be dynamically modified based on the magnitude of $|dP/dV|$[14][6]. Larger derivative values indicate the system's operating state deviates significantly from the optimal MPPT position, permitting increased step magnitudes to accelerate convergence. This adaptive strategy maintains operational stability while enhancing tracking efficiency. Second, given the algorithm's reliance on sensor measurements, implementing digital filtering techniques to process the raw data could improve measurement precision. Enhanced data quality enables more accurate theoretical MPPT calculations, narrowing the gap between predicted and actual maximum power points. Nevertheless, such enhancements inevitably raise hardware expenses, requiring users to carefully evaluate the cost-benefit ratio before implementing accuracy improvements.

2.3 Constant Voltage (CV) method

The Constant Voltage (CV) approach operates on a fundamentally distinct principle compared to conventional methods like P&O and INC. This technique eliminates the need for real-time tracking mechanisms, instead relying on a predefined empirical parameter derived from extensive photovoltaic system testing. Research reveals that while Maximum Power Point (MPP) positions fluctuate with irradiance (G) and temperature (T) variations, the associated voltage V_{mpp} typically remains confined within narrow operational boundaries. Empirical observations further indicate that V_{mpp} demonstrates a consistent proportionality to the open-circuit voltage (V_{oc}) under prevailing atmospheric conditions, as mathematically expressed in formula (12).

$$V_{mmp} \approx k \cdot V_{oc} \tag{12}$$

The proportionality coefficient k in this relationship generally maintains fixed values ranging from 0.71 to 0.78 across most operational scenarios. This methodology's theoretical foundation stems from the inherent electrical behavior of photovoltaic cells, where output characteristics approximately conform to the diode equation's predictions as shown in equation (13).

$$V \approx \frac{nKT}{q} \cdot \ln \frac{I_{ph-I}}{I_0} \tag{13}$$

The parameter "n" represents the ideality factor (ranging from 1 to 2, accounting for non-ideal characteristics), while "k" denotes the Boltzmann constant. The photocurrent "I_{ph}" varies with incident irradiance intensity, and "I_0" indicates the diode's reverse saturation current. The system's output current is symbolized as "I". Under open-circuit operation conditions where current flow ceases (I=0), the governing equation undergoes simplification to formular (14).

$$V \approx \frac{nkT}{q} \cdot \ln \frac{I_{ph}}{I_0} \tag{14}$$

As previously established, the photogenerated current (Iph) exhibits a direct proportionality to incident solar radiation intensity. An elevation in photogenerated current enhances the logarithmic term ln (Iph/I0) due to its inherent monotonic characteristics. This mathematical relationship directly influences the open-circuit voltage (Voc) through its multiplicative effect, resulting in corresponding voltage augmentation. Consequently, the correlation between Voc and irradiation intensity manifests logarithmic behavior. Following the principles outlined in equation (1), the resultant electrical power (P) demonstrates significant dependence on Voc parameters. Furthermore, empirical observations reveal that maximum power point voltage (Vmpp) maintains a near-constant proportionality coefficient relative to Voc, establishing the latter as a reliable control reference. Practical implementation involves acquiring Voc measurements through scheduled intermittent sampling procedures, followed by Vmpp computation using equation (12) parameters. Subsequent operational voltage regulation based on these derived references ensures sustained proximity to optimal power generation conditions within the photovoltaic system.

Photovoltaic systems exhibit a characteristic where maximum power point voltage (Vmpp) maintains a relatively stable ratio to open-circuit voltage (Voc) across varying operational conditions. This relationship persists despite Voc's inherent dependence on both solar irradiance levels and ambient temperature.

The operational methodology can be systematically outlined through these sequential phases:

$$V_{ref} = k \cdot V_{oc} \tag{15}$$

System calibration protocol. During startup sequences or periodic maintenance intervals, the system initiates a calibration procedure through controller commands. This process involves temporarily disconnecting the photovoltaic modules from the load circuit using switching components, enabling precise measurement and storage of instantaneous open-circuit voltage values (V_{oc}) under prevailing environmental conditions. A predetermined coefficient k, established through prior system configuration, facilitates reference voltage calculation through the application of equation (15).

Control Implementation. The regulation mechanism modulates the duty ratio (D) in power conversion circuits like Buck or Boost topologies, ensuring photovoltaic modules maintain consistent operational voltage aligned with the computed V_{ref} benchmark.

Adaptive recalibration. To compensate for open-circuit voltage (V_{oc}) deviations induced by thermal variations, the control architecture initiates scheduled recalibration cycles to refresh the reference voltage parameters.

This approach demonstrates operational superiority over conventional techniques through simplified implementation. By eliminating computationally intensive operations and minimizing code complexity, the algorithm achieves high stability with limited processing requirements. Rather than employing iterative adjustment procedures that cause output fluctuations, the methodology directly applies deterministic equations for decision-making. This design characteristic enhances immunity to environmental transients compared to perturbation-based maximum power point tracking strategies, while maintaining steady-state performance through formula-driven voltage regulation.

Nevertheless, this approach continues to face multiple limitations. The oversimplified algorithmic framework and rigid maintenance of predetermined k coefficients contribute to substantial inaccuracies in maximum power point (MPP) localization. Temperature fluctuations further influence the k parameter, yet the CV methodology erroneously treats this variable as static, exacerbating measurement discrepancies. The requirement for temporary output disconnection during sampling introduces unavoidable power wastage, with repeated sampling intervals amplifying energy dissipation. Operational efficiency demonstrates critical dependence on precise k-value determination - any miscalculations arising from improper initialization or material degradation over time directly compromise system performance.

This approach, characterized by its affordability and limited precision, is not ideal for specialized implementations or high-energy systems like large-scale charging infrastructures. Its practical value emerges in environments with minimal thermal fluctuations, where reduced operational complexity aligns with performance requirements. Under stable thermal conditions, periodic V_{oc} measurements can be minimized, thereby mitigating energy losses while ensuring the chosen k parameter will more accurately reflect actual operating conditions. The economical nature of this methodology maintains its viability for budget-sensitive deployments where moderate precision is acceptable, particularly in cost-driven applications prioritizing functional adequacy over measurement sophistication.

Scholars have developed multiple enhancement strategies for this approach [15]. A primary modification involves integrating temperature sensors to dynamically calibrate the k-value based on thermal measurements, thereby enhancing the accuracy of maximum power point (MPP) estimation [16]. An alternative strategy focuses on tracking ambient temperature variations - significant fluctuations trigger more frequent updates, while minor changes allow for reduced refresh rates. A third approach merges the technique with perturb-and-observe algorithms, introducing dynamic voltage adjustments near the CV-determined V_{ref} reference point to achieve precise MPP tracking [17,18]. These optimizations, however, require additional hardware components and more sophisticated control logic, potentially compromising the fundamental cost-effectiveness advantage of the CV methodology and creating implementation challenges in practical applications.

3 Conclusion

This study examines and contrasts three conventional MPPT techniques: Perturb and Observe (P&O), Incremental Conductance (INC), and Constant Voltage (CV) approaches. Each methodology demonstrates distinct strengths and weaknesses. The P&O approach, known for its cost-effectiveness and straightforward implementation, suffers from persistent oscillations under stable conditions and may produce erroneous tracking decisions during rapid solar irradiance fluctuations. The INC algorithm achieves superior precision and enhanced dynamic response capabilities, though it demands more sophisticated computational resources and high-precision sensing equipment, consequently elevating system costs. The CV technique maintains operational simplicity and minimal implementation expenses, yet its effectiveness is constrained by the predetermined proportionality constant k, rendering it primarily applicable to less demanding operational environments.

Enhancement techniques have been developed for these three methodologies, including adaptive step-size regulation, signal processing filters, and combined computational approaches. These innovations seek to optimize the trade-off between performance precision, operational effectiveness, and implementation expenses. Operational selection of MPPT techniques should consider specific implementation contexts, installation dimensions, and meteorological factors. In scenarios prioritizing affordability for compact installations, the constant voltage method remains functionally applicable. For industrial-grade or specialized applications, optimized perturbation-observation or incremental conductance variants demonstrate superior adaptability.

Maximum power point tracking continues to serve as a pivotal innovation for optimizing solar energy harvesting and minimizing power dissipation. Emerging investigations are likely to concentrate on sophisticated adaptive methodologies incorporating intelligent control systems, including probabilistic reasoning frameworks, deep learning architectures, and predictive analytics models. Such next-generation solutions could potentially enhance operational robustness, system resilience, and photovoltaic conversion effectiveness when deployed in dynamic meteorological conditions with multiple fluctuating parameters.

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