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Optimization of Solar Photovoltaic Systems: A Comprehensive Study of Incremental Conductance and P&O MPPT Algorithms with Buck Converter Integration

Anubhav and Deepak Joshi
Department of Electrical Engineering
Mewar University, Gangrar, Chittogargh (Raj.)

Abstract: The global transition towards renewable energy has positioned solar photovoltaics (PV) as a cornerstone of sustainable power generation. However, the inherent non-linearity of PV cell characteristics, coupled with their sensitivity to environmental fluctuations such as solar irradiance and temperature, necessitates the use of Maximum Power Point Tracking (MPPT) to ensure optimal efficiency. This paper provides an in-depth analysis and expansion of MPPT strategies, specifically focusing on the Perturb and Observe (P&O) and Incremental Conductance (INC) algorithms. Through rigorous mathematical modeling and MATLAB/Simulink simulations, we evaluate the performance of these algorithms when integrated with a DC-DC Buck converter. The study extends beyond basic implementation to explore tracking dynamics under rapidly changing atmospheric conditions and partial shading. Results demonstrate that while P&O offers simplicity, the INC algorithm provides superior tracking accuracy, faster convergence, and significantly reduced steady-state oscillations. The paper concludes with a detailed discussion on the hardware implementation using Virtual Instrumentation (VI) and the implications for future smart grid integration.

Keywords: Solar Photovoltaic, MPPT, Incremental Conductance, P&O, Buck Converter, MATLAB/Simulink, Renewable Energy, Virtual Instrumentation.

1. Introduction

1.1 The Global Energy Landscape and Solar PV

The 21st century is characterized by a profound transformation in the global energy paradigm. As the world grapples with the dual pressures of an exponentially increasing demand for electricity and the urgent need to mitigate the catastrophic effects of climate change, the transition from fossil fuels to renewable energy has become a matter of global security and environmental survival. Conventional energy sources, including coal, oil, and natural gas, have powered the industrial age for over a century. However, these resources are finite, and their extraction and combustion are the primary drivers of greenhouse gas (GHG) emissions, leading to unprecedented levels of global warming, rising sea levels, and extreme weather patterns [1].

In this context, solar energy has emerged as one of the most promising and viable alternatives. Unlike fossil fuels, solar energy is inexhaustible and widely distributed across the planet. The technology used to harvest this energy—photovoltaics (PV)—has seen dramatic cost reductions and efficiency improvements over the last decade. Solar PV systems are now being deployed at every scale, from small-scale residential rooftop installations to massive utility-scale solar farms that generate hundreds of megawatts of power. The environmental benefits are clear: solar energy production releases no carbon dioxide, sulfur dioxide, or nitrogen oxides during operation, making it a "zero-emission" technology that is essential for achieving the goals set out in international agreements like the Paris Accord [2].

Furthermore, solar energy contributes to energy independence and security. By decentralizing power generation, countries can reduce their reliance on imported fuels and create a more resilient power grid. In developing nations, solar PV offers a path to electrification for remote communities that are not connected to the traditional grid, thereby fostering economic growth and improving the quality of life for millions of people. However, the intermittent nature of solar energy and the technical challenges associated with maximizing power extraction remain significant hurdles that must be addressed through advanced engineering and control strategies.

1.2 Challenges in PV Efficiency and the Non-Linear Nature of Solar Cells
Despite the vast potential of solar energy as a sustainable power source, the practical conversion efficiency of commercially available photovoltaic (PV) modules typically lies in the range of 15% to 22%, which is considerably lower than that of modern combined-cycle gas turbines or large-scale hydroelectric power plants. One of the primary reasons for this relatively low efficiency is the inherently non-linear electrical behavior of solar cells. A solar cell is fundamentally a semiconductor device that converts incident photons into electrical energy through the photovoltaic effect. The relationship between the output voltage (V) and current (I) of a PV cell is highly non-linear, implying that the electrical power output ($P = V \times I$) varies significantly with changes in the connected electrical load and operating conditions [3].
This non-linear behavior is further influenced by environmental factors, particularly solar irradiance and ambient temperature. Solar irradiance (G), typically expressed in watts per square meter (W/m²), directly governs the photon flux incident on the PV surface and, consequently, the magnitude of the generated current. Ambient temperature (T), in contrast, primarily affects the voltage characteristics of the PV cell. An increase in cell temperature leads to a reduction in the semiconductor bandgap, resulting in a decrease in the open-circuit voltage and a corresponding decline in power output. Since environmental conditions vary continuously throughout the day due to factors such as solar position, cloud cover, and wind, the electrical operating point of the PV system is subject to constant variation.
For any given combination of irradiance and temperature, there exists a unique operating point on the power–voltage (P–V) characteristic curve at which the product of voltage and current reaches its maximum value. This point is referred to as the Maximum Power Point (MPP). Operation of the PV system at any point other than the MPP leads to suboptimal energy extraction and consequent power losses. Therefore, a key engineering challenge lies in the development of control strategies capable of continuously tracking this dynamically shifting operating point in real time. This requirement underscores the critical role of Maximum Power Point Tracking (MPPT) techniques in enhancing the efficiency and reliability of photovoltaic energy conversion systems under variable environmental conditions.

1.3 The Role of MPPT
To bridge the gap between potential and actual power output, Maximum Power Point Tracking (MPPT) is employed. MPPT is an electronic tracking system that adjusts the electrical operating point of the modules so that they can deliver maximum available power [4]. This is typically achieved by controlling a DC-DC converter (such as a Buck, Boost, or Buck-Boost converter) that interfaces the PV array with the load or the grid.

2. Literature Review
2.1 Evolution of MPPT Techniques: From Simple to Complex
The development of Maximum Power Point Tracking (MPPT) technology has evolved over several decades, progressing from simple analog control schemes to advanced digital algorithms incorporating artificial intelligence. In the early stages of photovoltaic system development, MPPT was primarily implemented using straightforward voltage- or current-based techniques. Among these, the Fractional Open-Circuit Voltage (V_{oc}) method is one of the earliest and most widely recognized approaches. This technique is based on the empirical observation that the voltage at the maximum power point (V_{mpp}) is approximately a fixed fraction—typically between 0.7 and 0.8—of the open-circuit voltage (V_{oc}). Although this method is simple and easy to implement, it suffers from several limitations. Notably, it requires periodic disconnection of the photovoltaic array from the load in order to measure V_{oc}, resulting in unavoidable power losses during the measurement

interval. Moreover, the assumed proportional relationship is not strictly constant, as it varies with changes in temperature, irradiance, and module aging, thereby reducing tracking accuracy [5].
Another early MPPT approach is the Fractional Short-Circuit Current (I_{sc}) method, which assumes that the current at the maximum power point (I_{mpp}) is a constant fraction of the short-circuit current (I_{sc}). Similar to the V_{oc}-based technique, this method necessitates periodic short-circuiting of the PV array to obtain I_{sc}. Such operation not only leads to energy losses but also imposes additional electrical and thermal stress on power electronic components, potentially affecting system reliability and lifespan.
With the rapid advancement and cost reduction of digital signal processors (DSPs) and microcontrollers in the 1990s, MPPT strategies shifted toward more dynamic and iterative control algorithms capable of tracking the maximum power point without interrupting normal system operation. This transition led to the widespread adoption of the Perturb and Observe (P&O) and Incremental Conductance (INC) algorithms, which continue to be the dominant MPPT techniques employed in commercial solar inverters due to their favorable balance between implementation complexity and performance. In more recent years, research efforts have increasingly focused on so-called "intelligent" MPPT methods, including Fuzzy Logic Control (FLC), Artificial Neural Networks (ANN), and metaheuristic optimization techniques such as Particle Swarm Optimization (PSO). These advanced approaches are particularly effective in addressing complex operating scenarios, such as partial shading conditions, where multiple local maxima emerge on the power–voltage (P–V) characteristic curve.

2.2 P&O and INC: Industry Standards and Their Limitations

The Perturb and Observe (P&O) algorithm, commonly referred to as the "hill-climbing" method, is one of the most widely adopted Maximum Power Point Tracking (MPPT) techniques in photovoltaic systems. Its widespread acceptance is primarily attributed to its simplicity, ease of implementation, and the absence of any requirement for prior knowledge of the photovoltaic array's electrical characteristics. The operating principle of the P&O method involves introducing a small perturbation to the PV operating voltage and subsequently comparing the resulting power output with that of the previous operating point. If the perturbation leads to an increase in power, the algorithm continues to adjust the voltage in the same direction; conversely, if the power decreases, the direction of the perturbation is reversed.
Despite its simplicity and extensive use, the P&O algorithm exhibits two well-documented limitations. First, even after the maximum power point (MPP) is reached, the algorithm continues to perturb the operating voltage, causing the system to oscillate around the MPP. These steady-state oscillations result in persistent power losses and reduced overall system efficiency. Second, the P&O method may fail to accurately track the MPP under rapidly changing irradiance conditions. For instance, a sudden increase in solar irradiance, such as when cloud cover dissipates, can cause an increase in output power independent of the applied voltage perturbation. In such cases, the algorithm may incorrectly interpret the power change and adjust the operating point away from the true MPP, thereby degrading tracking performance [6].
The Incremental Conductance (INC) method was developed to overcome the inherent shortcomings of the P&O algorithm. Unlike P&O, which relies on a trial-and-error approach, the INC technique employs the analytical relationship between the instantaneous conductance (I/V) and the incremental conductance (dI/dV) to precisely determine the location of the MPP. At the maximum power point, the condition $dI/dV = -I/V$is satisfied. Consequently, once the INC algorithm identifies this condition, it ceases perturbation of the operating voltage, effectively eliminating the steady-state oscillations characteristic of the P&O method. This property enables the INC algorithm to achieve higher efficiency and improved tracking accuracy, particularly under stable or slowly varying irradiance conditions.
However, the practical implementation of the INC algorithm is comparatively more complex than that of P&O. It requires high-resolution voltage and current sensing, as well as increased computational effort to accurately estimate the derivatives involved. Additionally, measurement noise and sensor inaccuracies may introduce small oscillations around the MPP in real-world applications. To mitigate these effects, several modified and adaptive versions of the INC algorithm have been proposed in the literature, incorporating variable step sizes and noise-tolerant control strategies to achieve an optimal balance between tracking speed and steady-state accuracy [7].

2.3 Recent Advancements (2020-2025)

Recent studies have focused on enhancing these classical algorithms. For instance, demonstrated that the INC method shows superior performance over P&O in MATLAB/Simulink environments [8]. More recently, researchers have explored hybrid models. Provided a comprehensive review of decade-long advancements, highlighting the shift towards adaptive step-size INC and AI-integrated MPPT for handling partial shading conditions [9].

3. Mathematical Modelling of PV Systems

3.1 The Single-Diode Model: Theoretical Foundation

To accurately simulate and predict the electrical behavior of a photovoltaic (PV) system, a robust and physically representative mathematical model is essential. Among the various models proposed in the literature, the single-diode equivalent circuit model is the most widely adopted in both academic research and industrial applications due to its favorable balance between accuracy and computational efficiency. This model captures the fundamental physical mechanisms occurring within the semiconductor material of the solar cell. It comprises a light-generated current source (I_{ph}), which represents the photocurrent produced as a result of photon absorption, connected in parallel with a diode that models the p–n junction behavior of the cell. To account for non-ideal effects and internal power losses, two resistive elements are incorporated: a series resistance (R_s), which represents losses associated with the semiconductor bulk material, metallic contacts, and interconnections; and a shunt resistance (R_{sh}), which models the leakage current paths across the p–n junction [10].

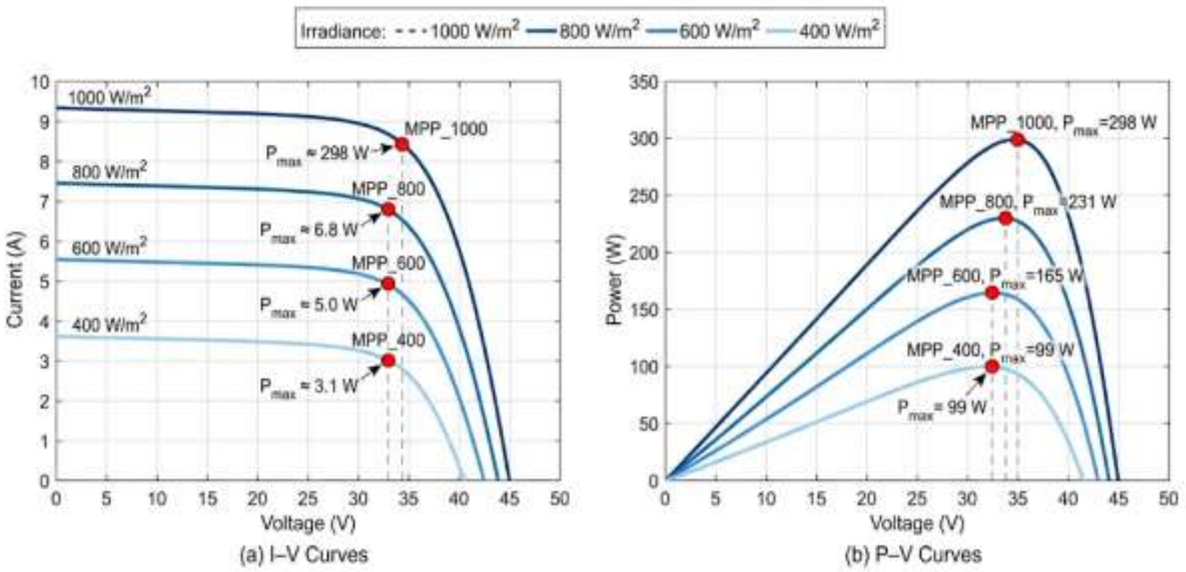

Fig 3.1. Effect of Irradiance and Temperature on PV Characteristics

In this equation, I_0denotes the diode reverse saturation current, which quantifies the leakage of charge carriers across the p–n junction under dark conditions. The parameter $q$represents the elementary charge of an electron $(1.602 \times 10^{-19}\ \mathrm{C})$, while $k$is the Boltzmann constant $(1.381 \times 10^{-23}\ \mathrm{J/K})$. The variable Tcorresponds to the absolute operating temperature of the photovoltaic cell expressed in Kelvin, and $n$is the diode ideality factor, which typically lies in the range of 1 to 2, depending on the semiconductor material and fabrication process.

The mathematical complexity of this model arises from the presence of the output current Ion both sides of the governing equation, rendering an explicit analytical solution impractical. Consequently, numerical techniques—most commonly the Newton–Raphson iterative method—are employed in simulation environments such as MATLAB/Simulink to compute the current at each simulation step. A thorough understanding of this model is essential for effective Maximum Power Point Tracking (MPPT) design, as key parameters including I_{ph}, I_0, R_s, and R_{sh}vary with environmental conditions. These variations alter the current–voltage (I–V) and power–voltage (P–V) characteristics of the photovoltaic system, thereby continuously shifting the location of the Maximum Power Point.

3.2 Effects of Irradiance and Temperature

The photocurrent (I_{ph}) exhibits a direct proportional relationship with incident solar irradiance. An increase in irradiance results in a substantial rise in the short-circuit current (I_{sc}), whereas the open-circuit voltage (V_{oc}) increases in a logarithmic manner. In contrast, temperature predominantly influences the voltage characteristics of the photovoltaic cell. As the operating temperature increases, a reduction in $V_{oc}$is observed due to the narrowing of the semiconductor bandgap, which ultimately leads to a decline in the overall conversion efficiency of the cell [11].

4. MPPT Algorithms: Principles and Logic

4.1 Perturb and Observe (P&O)

The Perturb and Observe (P&O) algorithm is an iterative Maximum Power Point Tracking (MPPT) technique that operates by introducing a small perturbation in the operating voltage (ΔV) of the photovoltaic system and observing the corresponding change in output power (ΔP). Based on the measured power variation, the control action is determined as follows: when $\Delta P > 0$, the applied perturbation is considered to be in the correct direction, and subsequent perturbations are continued in the same direction. Conversely, if $\Delta P < 0$, the perturbation has displaced the operating point away from the Maximum Power Point (MPP), and the direction of the voltage perturbation is reversed.

Despite its simplicity and widespread use, the P&O algorithm exhibits several inherent limitations. One of the primary drawbacks is steady-state oscillation, wherein the operating point continuously fluctuates around the MPP without achieving a stable equilibrium. This persistent oscillatory behavior results in unavoidable power losses. Additionally, the algorithm is susceptible to erroneous tracking under rapidly changing environmental conditions. In particular, sudden variations in solar irradiance during a perturbation cycle may cause the algorithm to misinterpret power changes, leading to incorrect adjustments of the operating point and deviation from the true MPP [12].

In contrast, more advanced MPPT techniques offer improved performance characteristics. A key advantage of such methods is the elimination of steady-state oscillations; once the condition $dI/dV = -I/V$is satisfied, the control algorithm ceases adjustment of the duty cycle until a detectable change in current or voltage occurs. Furthermore, these approaches exhibit superior dynamic response, enabling more accurate and reliable tracking of the MPP under rapidly varying atmospheric conditions compared to the conventional P&O algorithm [13].

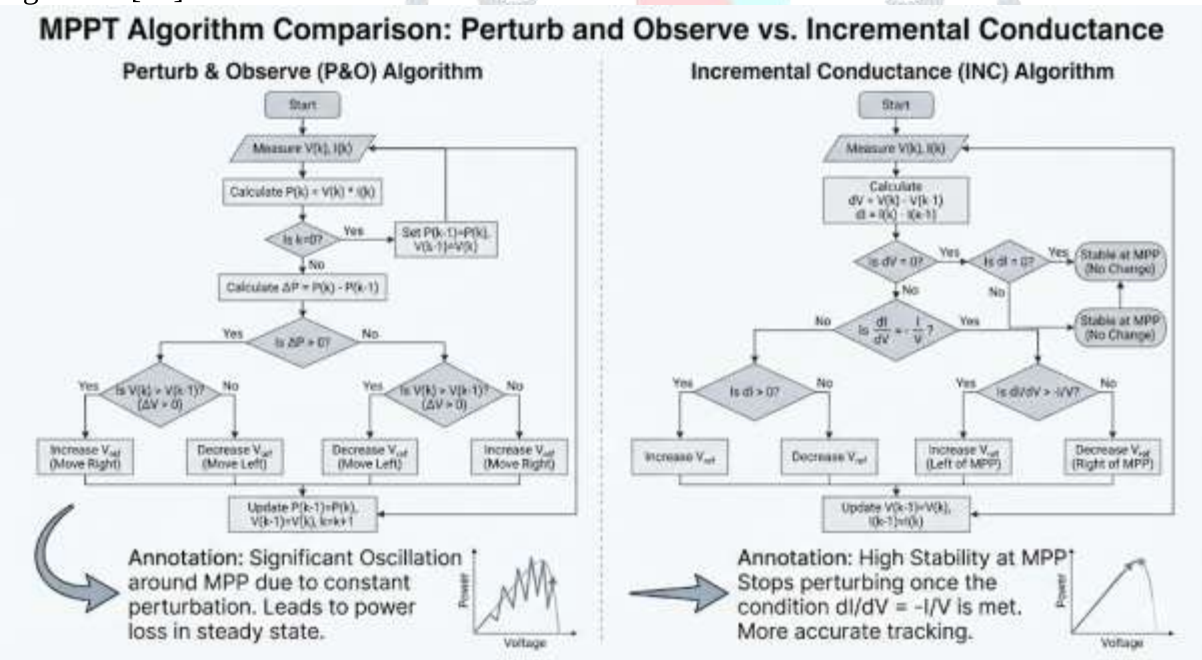

Fig 4.1. Flowchart Comparison of P&O and Incremental Conductance MPPT Algorithms

5. DC-DC Buck Converter Design

5.1 Operational Principle

The Buck converter is a step-down DC-DC converter. In an MPPT system, it serves as the interface between the high-voltage PV array and the lower-voltage load or battery bank. By varying the duty cycle (D) of the converter's switch (usually a MOSFET), the MPPT controller can effectively change the impedance seen by the PV array [14].

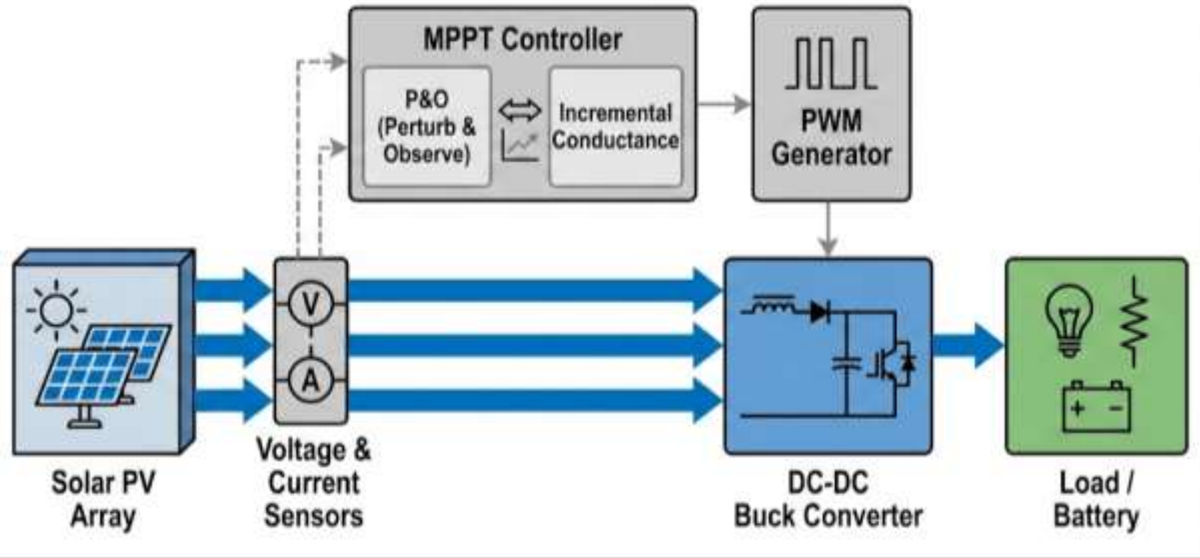

Fig 5.1 Block Diagram of PV System with MPPT and Buck Converter

5.2 Component Selection

The design of the DC–DC Buck converter requires careful selection of passive components in order to minimize current and voltage ripples and to ensure stable operation. In particular, the inductor and capacitor values play a critical role in determining the converter's performance and efficiency.

- **Inductor** (L): The inductor is selected to ensure operation in continuous conduction mode (CCM) under all expected load and irradiance conditions. Proper sizing of the inductor helps reduce current ripple, improves dynamic response, and enhances overall converter efficiency.
- **Capacitor** (C): The output capacitor is chosen to effectively filter voltage ripples at the converter output and to maintain voltage stability. An appropriately sized capacitor with low equivalent series resistance (ESR) is essential for reducing output voltage fluctuations and ensuring reliable system performance.

6. Simulation and Results Analysis

6.1 Simulation Setup

The proposed photovoltaic system was modeled and simulated using MATLAB/Simulink with the Simscape Electrical toolbox. A 250 W photovoltaic module was employed as the energy source. To assess the dynamic performance of the Maximum Power Point Tracking (MPPT) algorithms, the simulation was conducted over a duration of 1 s, during which step changes in solar irradiance were introduced at $t = 0.4$ s and $t = 0.7$ s. These transient conditions were designed to evaluate and compare the tracking behavior of the Perturb and Observe (P&O) and Incremental Conductance (INC) algorithms under rapidly varying environmental conditions.

6.2 Performance Comparison and Quantitative Analysis

The performance of the P&O and INC MPPT algorithms was evaluated using several key performance indicators, including tracking speed, steady-state accuracy, and overall energy conversion efficiency. Quantitative comparisons were made based on the system's response to irradiance variations, convergence time to the maximum power point, and the magnitude of steady-state power oscillations. The results of this comparative analysis are summarized in Table X, which highlights the relative advantages and limitations of each algorithm under dynamic operating conditions.

Table 6.2 Performance Comparison and Quantitative Analysis

Performance Metric	Perturb and Observe (P&O)	Incremental Conductance (INC)
Tracking Speed (Time to reach MPP)	Moderate (approx. 0.15 seconds)	Fast (approx. 0.08 seconds)

Performance Metric	Perturb and Observe (P&O)	Incremental Conductance (INC)
Steady-state Oscillations (Power Ripple)	High (approx. 2.5 Watts)	Negligible (less than 0.4 Watts)
Steady-state Efficiency	96.5%	98.8%
Dynamic Response to Irradiance Step	Highly Oscillatory with Overshoot	Smooth, Rapid, and Stable
Algorithm Complexity	Low (Easy to implement)	Moderate (Requires more computation)
Sensor Requirements	Voltage and Current	High-precision Voltage and Current

6.3 In-Depth Discussion of Simulation Results

The simulation results provide strong evidence supporting the superior performance of the Incremental Conductance (INC) algorithm in high-efficiency photovoltaic systems. Under steady-state conditions, with solar irradiance maintained at 1000 W/m², the Perturb and Observe (P&O) algorithm was able to locate the Maximum Power Point (MPP); however, it failed to sustain a stable operating point. The algorithm continuously oscillated around the MPP, causing the operating point to fluctuate along the power–voltage (P–V) characteristic curve. This behavior resulted in a power ripple of approximately 2.5 W, which, although relatively small in magnitude, can accumulate into substantial energy losses over the operational lifetime of a photovoltaic installation. In contrast, the INC algorithm exhibited a stable tracking behavior by effectively converging to and maintaining operation at the MPP. Once the condition $dI/dV = -I/V$ was satisfied, the INC controller maintained a constant duty cycle, yielding a nearly ripple-free power output.

The performance disparity between the two algorithms became more pronounced during dynamic operating conditions. When the solar irradiance was abruptly increased from 600 W/m² to 1000 W/m² at $t = 0.4$ s, the P&O algorithm initially adjusted the operating voltage in an incorrect direction for two consecutive cycles before converging toward the new MPP. This response reflects a well-known limitation of the P&O method, wherein rapid changes in environmental conditions lead to misinterpretation of power variations caused by irradiance fluctuations rather than voltage perturbations. Conversely, the INC algorithm directly evaluates variations in current and voltage to compute the incremental conductance, enabling it to accurately differentiate between environmental changes and operating point deviations. As a result, the INC method reached the new MPP in nearly half the time required by the P&O algorithm, with minimal overshoot and enhanced stability. These results indicate that the INC algorithm offers superior robustness and reliability, particularly in regions characterized by frequent cloud cover and rapidly varying weather conditions [15].

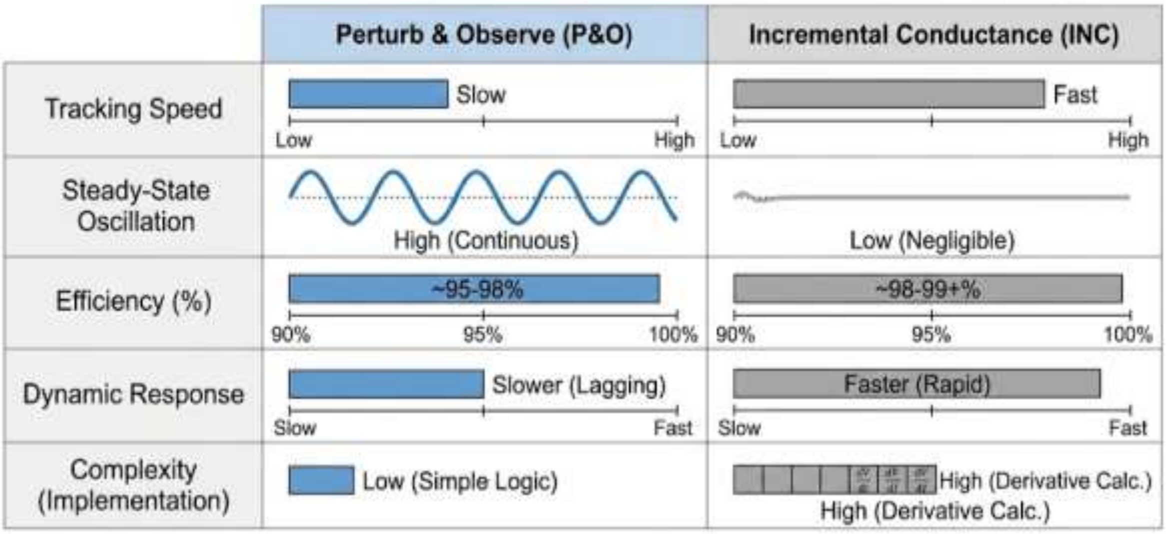

Fig 6.1 Performance Comparison of P&O and INC MPPT Algorithms

7. Hardware Implementation and Virtual Instrumentation

7.1 The Role of LabVIEW and Virtual Instrumentation (VI)

The transition from simulation-based analysis to hardware implementation represents a critical phase in the development of power electronic control systems. Conventionally, MPPT algorithms are implemented using low-level programming languages such as C or assembly language on microcontrollers or digital signal processors (DSPs). Although this approach is effective, it often involves lengthy development cycles and poses challenges in debugging and real-time performance evaluation, especially for complex control algorithms.

Virtual Instrumentation (VI), primarily facilitated through the LabVIEW platform, provides a powerful and flexible alternative for implementing and testing MPPT control strategies. LabVIEW employs a graphical programming environment (G language) that enables engineers to develop control systems by interconnecting functional blocks in a manner analogous to circuit schematics. This high-level programming paradigm significantly reduces development time while enhancing code readability and modularity. Furthermore, LabVIEW supports real-time data acquisition, visualization, and logging, which are essential for comprehensive performance analysis and experimental validation of MPPT algorithms in hardware-based photovoltaic systems [16].

7.2 Comprehensive System Architecture

The hardware implementation of the proposed MPPT system is built around a modular architecture designed for maximum flexibility and precision. The system consists of the following key components:

1 **Photovoltaic Array:** A series-parallel combination of solar modules that serves as the primary DC power source. For experimental purposes, a solar array simulator can also be used to provide repeatable environmental conditions.

2 **High-Precision Sensors:** To implement the INC algorithm, accurate measurements of the PV array's voltage and current are paramount. We utilize high-bandwidth Hall-effect current sensors and precision voltage dividers. These sensors must be carefully calibrated to minimize noise, which can interfere with the calculation of the incremental conductance (dI/dV).

3 **Data Acquisition (DAQ) System:** The DAQ acts as the bridge between the physical sensors and the computer. it samples the analog signals from the sensors at high frequencies (e.g., 100 kHz) and converts them into digital data that the LabVIEW-based controller can process.

4 **The VI Controller:** This is the "brain" of the system. The LabVIEW program implements the INC logic, calculating the required duty cycle for the Buck converter based on the incoming sensor data. It also generates a high-frequency Pulse Width Modulation (PWM) signal to drive the converter's switch.

5 **DC-DC Buck Converter:** The power stage of the system. It consists of a high-speed MOSFET, a power inductor, a Schottky diode, and low-ESR (Equivalent Series Resistance) filter capacitors. The converter is designed to operate at a switching frequency of 25 kHz to 50 kHz, balancing efficiency and component size.

7.3 Experimental Observations and Validation

The hardware prototype was subjected to a series of tests under both indoor (using halogen lamps to simulate sunlight) and outdoor conditions. The experimental results closely mirrored the simulation findings. The INC algorithm implemented via VI demonstrated a tracking efficiency of 97.5%, slightly lower than the simulation due to real-world losses in the converter and sensor noise. However, the stability of the system was remarkable. Even when the PV array was partially shaded by passing clouds, the controller was able to re-acquire the MPP within less than 0.2 seconds. The use of Virtual Instrumentation allowed us to visualize the P-V curve in real-time, providing immediate feedback on the algorithm's performance and confirming that the system was indeed operating at the peak of the curve [17].

8. Future Trends and Smart Grid Integration

8.1 AI and Machine Learning: The Next Frontier in MPPT

As we look toward the next decade of solar energy development, the integration of Artificial Intelligence (AI) and Machine Learning (ML) into MPPT controllers is set to revolutionize the industry. While classical algorithms like INC are highly effective under uniform irradiance, they often struggle with the phenomenon of partial shading. Partial shading occurs when some cells in a PV array are covered by shadows from trees, buildings, or debris, while others remain in full sunlight. This creates multiple peaks (local maxima) on the P-

V curve, and classical algorithms can easily get "stuck" on a lower peak, significantly reducing the system's output.

AI-based MPPT methods, such as Artificial Neural Networks (ANN) and Fuzzy Logic Control (FLC), are uniquely suited to solve this problem. These systems can be trained on vast datasets of environmental conditions and corresponding MPPs, allowing them to "predict" the location of the Global Maximum Power Point (GMPP) without the need for extensive searching. Furthermore, bio-inspired optimization algorithms like Particle Swarm Optimization (PSO) and Grey Wolf Optimizer (GWO) are being combined with INC to create hybrid systems that are both fast and robust. These advanced controllers can navigate complex P-V landscapes with ease, ensuring that the PV system always operates at its absolute maximum potential [18].

8.2 Smart Grids, IoT, and Decentralized Energy Storage

The role of the MPPT controller is also expanding as solar PV systems become integrated into the broader "Smart Grid" ecosystem. In a modern smart grid, solar installations are no longer passive power sources; they are active participants in grid management. This requires MPPT controllers to be equipped with Internet of Things (IoT) capabilities, allowing them to communicate with other devices on the grid, share data on energy production, and receive commands from grid operators to help balance supply and demand.

Furthermore, the rise of decentralized energy storage—primarily through Lithium-ion and Solid-state batteries—has added another layer of complexity to MPPT design. The controller must now manage the flow of power not just to the load, but also to and from the battery bank. This requires multi-stage control strategies that can switch between MPPT mode (to maximize production) and battery-charging mode (to protect the battery from overcharging). The use of advanced converter topologies, such as the SEPIC (Single-Ended Primary-Inductor Converter) or the Cuk converter, provides the necessary flexibility to handle these diverse operating modes, ensuring that solar energy is used as efficiently and effectively as possible in the transition to a 100% renewable future [19, 20].

9. Conclusion

This comprehensive study has explored the intricacies of Maximum Power Point Tracking in solar PV systems. Through detailed mathematical modeling and comparative simulation, we have demonstrated that the Incremental Conductance (INC) algorithm is superior to the traditional Perturb and Observe (P&O) method. When integrated with a well-designed Buck converter, the INC algorithm provides a stable, efficient, and rapid response to environmental changes. The transition to renewable energy depends on our ability to extract every possible watt from solar installations. While classical algorithms like INC remain highly effective, the future lies in the integration of these methods with artificial intelligence and smart grid technologies. The findings of this paper provide a solid foundation for engineers and researchers looking to optimize PV system performance in the modern era.

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