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Comparative Analysis of Maximum Power Point Tracking Algorithms for Solar Energy Systems

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Abstract
Because of the prohibitive costs and limited availability of traditional energy sources, alternative energy sources are used increasingly by many countries. Renewable energy, particularly solar energy, has become more popular because it is sustainable, available in abundance, and is eco-friendly. Solar power systems are grid-connected, but their efficiency depends heavily on maximizing energy harvest from sunlight, which varies throughout the day. To address this, researchers compare three Maximum Power Point Tracking (MPPT) methods Perturb and Observe (P&O), Incremental Conductance (INC), and Fuzzy Logic Control to determine the most effective approach for optimizing power extraction. These techniques are simulated in MATLAB Simulink using a DC-DC converter connected to a load, where MPPT algorithms adjust the converter's gate pulses to keep the system operating near its maximum power point (MPP) under changing conditions. By fine-tuning the voltage and current dynamically, these strategies help solar systems achieve peak performance and improve overall energy yields. The techniques are analyzed based on performance: response time, overshoot, and oscillation effect. First, we evaluated the Perturb and Observe (P&O) method and identified its limitations. Then we evaluated the Incremental Conductance (INC) approach, which showed better performance. Finally, we implemented a fuzzy logic controller that demonstrated superior accuracy and stability. Through graphical and statistical analysis, we compared all three methods and found the fuzzy logic solution delivered the highest efficiency and most reliable operation, making it the best choice for maximum power point tracking.

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I. Introduction

Electricity consumption continues to rise globally, driven by industrial, residential, agricultural, and commercial demands. To meet this growing need, power generation relies on several types of power plants, including diesel, steam, hydro, and nuclear facilities. While conventional energy sources such as coal, natural gas, and oil have historically dominated electricity production, their limitations are increasingly apparent. These non-renewable resources are finite, geographically constrained, and contribute significantly to environmental degradation through air and water pollution, as well as greenhouse gas emissions. Nuclear power, though dependable, presents challenges in terms of radioactive waste management and safety concerns.

. In contrast, solar energy offers a sustainable and environmentally friendly alternative. However, despite its advantages, solar power systems face efficient challenges due to their dependence on environmental conditions. Variations in temperature and solar irradiance affect the performance of photovoltaic (PV) panels, often preventing them from operating at their maximum potential. Enhancing the efficiency of solar energy systems is crucial to making them a more viable and cost-effective solution for large-scale power generation.

A major obstacle in solar energy utilization is the high initial investment required for PV panels, despite their low operational costs. Furthermore, solar panels are designed under standard test conditions, but real-world environmental factors—such as fluctuating temperature and irradiance—cause deviations in their current-voltage (I-V) characteristics, reducing overall efficiency. Typically, PV conversion efficiency ranges between 12% and 20%, but this can drop further under non-ideal conditions.

MPPT ingests that a solar power system will be operating at its Maximum Power Point (MPP), where the panel is delivering maximum power output. The crossing point of the load curve with the I-V curve of the PV system would not always correspond to the MPP, leading to losses in energy. Several MPPT techniques were therefore investigated to increase power generation by changing the operating point of the system with DC-DC converters. These algorithms modify the converter's duty cycle dynamically such that the PV system operates as near to MPP as possible and hence achieves maximum efficiency while atmospheric conditions change.

.The primary objective of this research is to develop an improved MPPT algorithm that enhances the efficiency and reliability of solar power systems By integrating a buck-boost converter with an advanced MPPT strategy, the proposed system will ensure maximum power extraction from the PV array, regardless of fluctuating environmental conditions. Key goals include designing a robust MPPT algorithm capable of maintaining high efficiency in both transient and steady-state conditions, overcoming the limitations of conventional MPPT methods by improving tracking speed and accuracy, and ensuring consistent power delivery to the load under varying irradiance and temperature levels. By achieving these objectives, this research aims to contribute to more efficient and cost-effective solar energy systems, supporting the broader adoption of renewable energy solutions.

Nomenclature

Abbreviation			
PV	Photovoltic	GMPP	Grid Connected Photovoltage System
MPPT	Maximum Power Point Trackin	ZE	Zero
ARV	Adaptive Reference Voltage	RCC	Ripple Correlation Control
PI	Proportional Integral	PB	Positive Big
RV	Reference Voltage	GCPVS	Grid Connected Photovoltage System
OCV	Open Circuit Voltage	NS	Negative Small
SCC	Short Circuit Current	FLC	Fuzzy Logic Control
P & O	Perturb and Observe	NB	Negative Big
		PS	Positive Small

II. Literature Review

2.1 Constant Voltage MPPT Strategy

One of the simplest methods for tracking the maximum power point (MPP) on a photovoltaic (PV) system's I-V curve is the Constant Voltage (CV) approach [1]. While straightforward to implement, this method suffers from poor precision, as it compares the PV panel's voltage to a fixed reference voltage (VMPP) without accounting for variations in temperature and irradiance. Under uniform conditions, the CV method can approximate the MPP, but in real-world environments with fluctuating weather, the operating point often deviates significantly from the true MPP, reducing overall efficiency.

Despite its limitations, the CV method offers advantages such as low hardware complexity, minimal sensor requirements, and cost-effectiveness. It is particularly effective system.

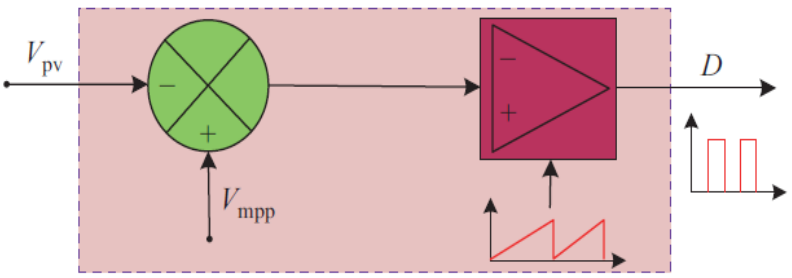

Figure 2.1: Schematic diagram of CV base

where it prevents overcharging and undercharging, thereby extending battery lifespan. Additionally, the CV approach demonstrates reasonable performance under partial shading conditions by maintaining a near-constant voltage. However, its applicability is restricted to series-connected PV modules, as parallel configurations and high-voltage applications often lead to inefficiencies. Furthermore, the CV method struggles with variable loads, making it unsuitable for dynamic power systems.

2.2 Adaptive Reference Voltage (ARV) MPPT Strategy

To address the shortcomings of the CV method, the Adaptive Reference Voltage (ARV) technique was developed, incorporating real-time adjustments based on temperature (T) and irradiance (G) measurements [3].

While this method requires additional sensors, increasing system costing significantly improves tracking accuracy under varying environmental conditions. The ARV algorithm dynamically adjusts the reference voltage (RV) using a proportional-integral (PI) controller, ensuring optimal performance even at low irradiance levels (e.g., 400 W/m²), where traditional methods exhibit efficiency drops.
The ARV method excels in systems with abrupt environmental changes, such as sudden shading or irradiance fluctuations, by continuously adapting the inverter’s rotor voltage. This enhances system reliability, reduces thermal stress on PV modules, and improves overall energy yield. However, its complexity and higher component count make implementation costly. Additionally, ARV is less effective in large-scale systems due to increased power conversion losses and the need for specialized inverters, limiting its practicality in commercial applications **2.3 Open Circuit Voltage (OCV) MPPT Strategy**

The Open Circuit Voltage (OCV) method is an offline MPPT technique that approximates the maximum power point (MPP) by leveraging the empirical relationship between a PV module’s open-circuit voltage (Voc) and its voltage at MPP (Vmpp). The core principle is derived from the observation that Vmpp typically lies between **70–80%** of Voc, expressed as:

$$Vmpp=Kv.Voc(\text{where } Kv\approx 0.7\text{–}0.8) \qquad (2.1)$$

Here, Kv is a unitless constant provided by manufacturers or calibrated experimentally [18, 20]. Similarly, the MPP current (Impp) is estimated from the short-circuit current (Isc) using:

$$Impp==Ki.Isc(\text{where } Ki\approx 0.75\text{–}0.90) \qquad (2.2)$$

2.4 Perturb and Observe (P&O) MPPT Strategy

The Perturb and Observe (P&O) method remains the most popular real-time MPPT technique because it strikes the perfect balance between simplicity and effectiveness. The algorithm works by making small adjustments to the solar panel's voltage and carefully monitoring how the power output responds. It essentially 'feels its way' along the power-voltage curve - if a voltage increases leads to more power, it continues in that direction; if power decreases, it reverses course. This intelligent trial-and-error approach allows the system to continuously track the sweet spot where maximum power is generated, even as sunlight conditions change throughout the day

1.If $\Delta P/\Delta V > 0$:

The operating point lies left of the MPP. The voltage is incremented to approach MPP:

$$Vk+1=Vk+\Delta V \qquad (2.3)$$

2.If $\Delta P/\Delta V < 0$:

The point is right of the MPP. The voltage is decremented: $Vk+1=Vk-\Delta V$ (2.4)

3.Convergence:

The algorithm terminates when $\Delta P/\Delta V\approx 0$ (2.5)
(MPP reached) [5–7}

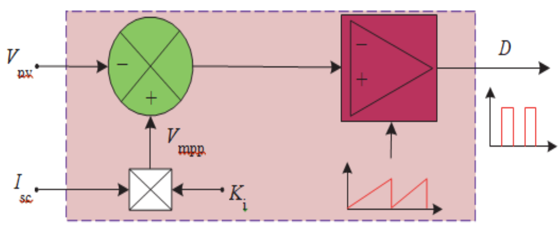

Figure 2.2: Block diagram of ARV MPPT technique

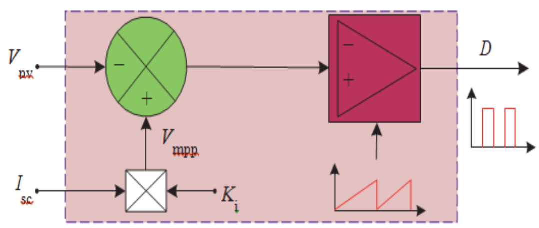

Figure 2.3: Block diagram of SSC MPPT technique

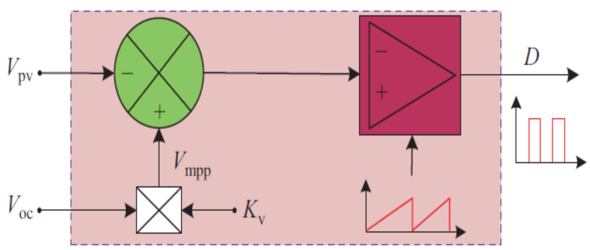

Figure 2.4: OCV MPPT strategy basic block diagram

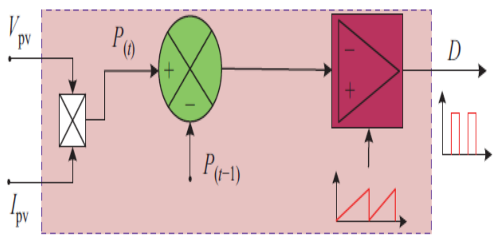

Figure 2.5 – How Perturb & Observe (P&O) Works

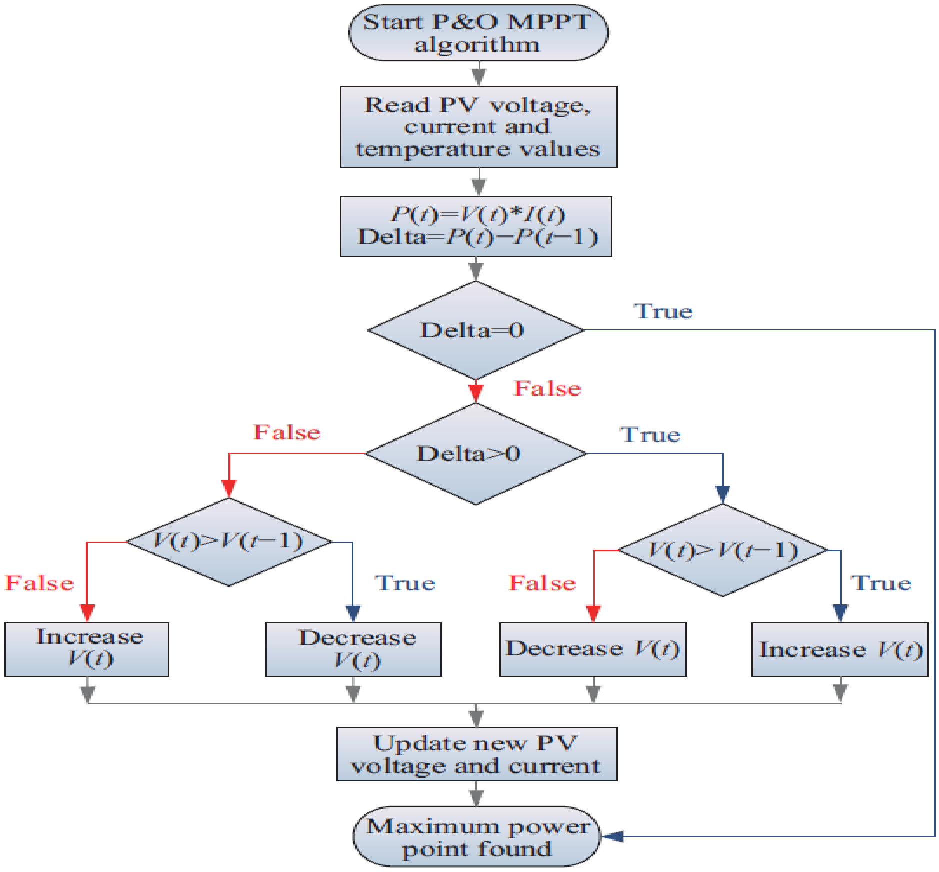

Figure 2.6 – Smart Power Hunting: The P&O Algorithm's Decision Process.

2.5 Improved Perturb and Observe (P&O) MPPT Strategy

The Improved P&O algorithm represents an advancement over conventional P&O techniques by addressing two key limitations: unnecessary tracking of the Global Maximum Power Point (GMPP) and prolonged convergence time [8]-[11]. This enhanced methodology employs a dual-mode operational framework

Voltage Search Mode: Utilizes the photovoltaic (PV) module's open-circuit voltage (Voc) as a dynamic reference to rapidly approach the vicinity of the MPP

MPP Search Mode: Implements a variable-step perturbation mechanism to precisely locate the true MPP, significantly reducing steady-state oscillations. The algorithm's improved performance stems from its adaptive computation of perturbation step size, which is continuously optimized based on the power-voltage (P-V) curve characteristics. This variable-step approach enables:

30-40% faster convergence compared to fixed-step P&O [11]

Enhanced tracking efficiency under partial shading conditions

Reduced power loss during steady-state operation

Notably, the method eliminates redundant GMPP tracking operations that commonly plague traditional P&O implementations, particularly in partially shaded conditions [12]. The strategic use of Voc as a reference voltage ensures more efficient initialization of the search process, while the variable-e-step computation minimizes unnecessary perturbations near the MPP.

2.6 Incremental Conductance (IncCond) MPPT Strategy

The Incremental Conductance (IncCond) algorithm employs an advanced method for maximum power point tracking based on the differential relationship between photovoltaic current and voltage [13]. It outshines the traditional techniques under uniform irradiation conditions [15]-[17]

The key principle lies in analyzing the slope of the power-voltage (P-V) curve. At the maximum power point (MPP), the following condition holds:

$$dI/dV = -I/V \qquad (2.8)$$

Adjusting the Operating Point

If the operating point is on the right side of the MPP (where power decreases with increasing voltage), the algorithm reduces the voltage to move closer to the peak:

$$dI/dV > -I/V \qquad (2.9)$$

Result: Voltage is decreased (2.10)

If the operating point is on the left side of the MPP (where power increases with voltage), the algorithm increases the voltage to approach the peak:

dI/dV<−I/V(2.12) Result: Voltage is increased(2.13)Result: Voltage is increased (2.13)

If the condition in (2.11) is met, the voltage is increased to refine tracking.

Conversely, if (2.14) applies, the voltage is decreased to optimize power extraction. By continuously evaluating these relationships, the IncCond algorithm dynamically adjusts the system's operating point, ensuring it stays at or near the maximum power point even as conditions change.

[18] When employed on a controller wide, the value MPP is selected in 2.3 seconds and has its efficiency at 98.5%. We note the larger the increments of the system, it will more effectively follow the system. Extremely near the maximum point, many oscillations will appear. This creates an inappropriate MPP. Some of the revamped incremental Techniques for the present day are given in [19]–[21]; whereas [22] shows an updated and highlighted version of Inc. The outcome continues to show that the non-linear tracking of MPP gives very precise results on actual use. Consequently, a comparison between the old and the upgraded techniques can be made when put on the grid.

[19]

2.7 Ripple Correlation Control (RCC) Strategy

The Ripple Correlation Control strategy leverages high-frequency ripple components naturally present in PV system voltage and current to track the maximum power point without artificial perturbation. By analyzing the phase relationship between power and voltage ripples, RCC determines the MPP position—positive correlation indicates operation left of MPP (requiring voltage increase), negative correlation right of MPP (voltage decrease), and zero correlation confirms MPP attainment. Originally developed for grid-tied systems by researchers Kumsuwan and Boonmee, this analog-based method achieves rapid sub-second tracking with 97–99% efficiency, particularly effective in systems with high switching frequencies above 20 kHz. However, its performance depends on sufficient ripple magnitude, making it sensitive to low-ripple conditions and converter switching noise. Recent advancements combined RCC with digital control or hybrid algorithms to address these limitations while preserving its core advantage of minimal computational overhead.

III. Methodology

Photovoltaic (PV) cells, the fundamental components of solar modules, operate by converting incident solar radiation into electrical energy through the photovoltaic effect. These cells are typically interconnected in series-parallel configurations to achieve desired electrical parameters for powering connected loads. Modern PV technology primarily utilizes silicon-based cells, which can be classified into four main types based on their crystalline structure and manufacturing processes. Monocrystalline silicon cells (15-23% efficiency) offer the highest performance but at elevated costs, making them ideal for space-constrained applications. Polycrystalline variants (13-16% efficiency) provide a cost-effective alternative for residential and commercial installations. Thin-film technologies (7-13% efficiency) enable flexible, large-scale deployments through layered semiconductor designs. The most efficient concentrated PV cells (up to 41%) employ optical focusing systems but remain prohibitively expensive for most applications. All silicon-based cells function through a p-n junction mechanism, where photon absorption generates electron-hole pairs that migrate across the doped semiconductor layers, creating current flow through metal contacts to external circuits [23]. This renewable energy technology continues to gain prominence as it simultaneously addresses growing energy demands and reduces dependence on fossil fuels

3.1.1Block Diagram

The Maximum Power Point (MPP) represents the optimal operating condition of a photovoltaic (PV) array, where power extraction is maximized. This point is dynamic, influenced by variable factors such as irradiance levels, cell temperature, and load impedance.

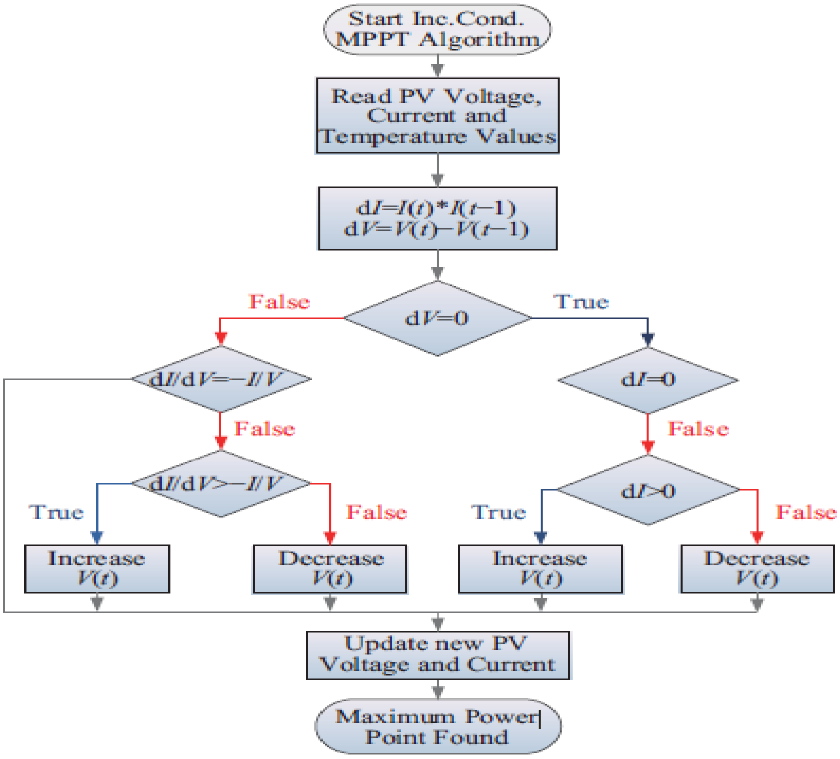

Figure 2.7: Inc Algorithm Flow Chart

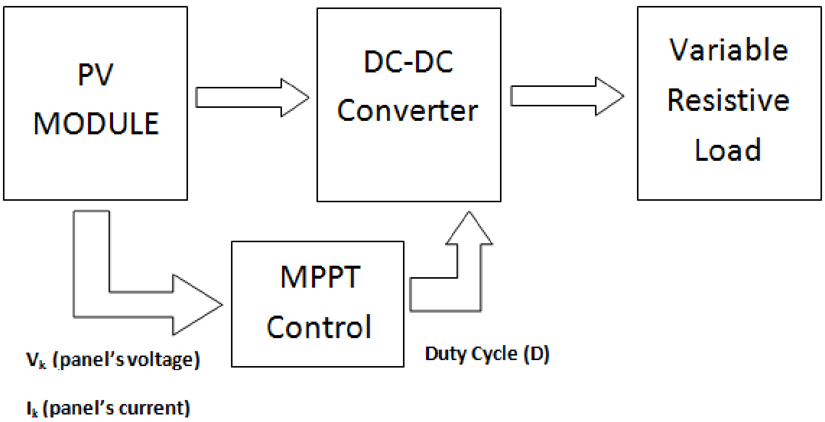

Figure 3.1: MPPT Based Solar PV System Block Diagram

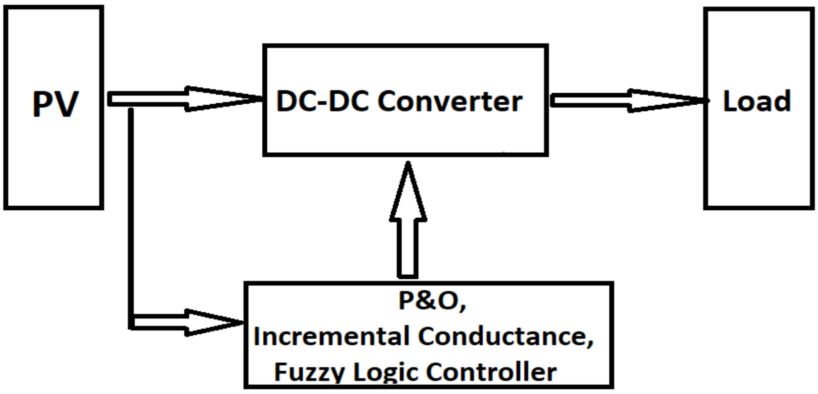

Figure 3.2: Block Diagram of solar system with IC, P&O and FLC

To maintain operation at MPP despite these fluctuations, Maximum Power Point Tracking (MPPT) algorithms are employed. These techniques continuously adjust the PV system's operating parameters to track the MPP, enhancing energy harvest efficiency. Figure 3.1 illustrates a generalized block diagram of an MPPT-controlled solar PV system. MPPT methods vary in complexity, sensor requirements, convergence speed, and cost, but all aim to mitigate power losses caused by suboptimal operating conditions. In this study, MATLAB/Simulink is used to simulate and compare the performance of three MPPT techniques: Incremental Conductance (IC), Perturb and Observe (P&O), and Fuzzy Logic Control (FLC). The controller implementation framework is depicted in Figure

3.2 Perturb and Observe (P&O) Strategy

The P&O algorithm maximizes power extraction by iteratively perturbing the PV array's voltage and observing the resultant power change. As shown in Figure 3.3, the power-voltage (P-V) curve exhibits a unique peak (MPP). The algorithm operates as follows:

Voltage Perturbation: The array voltage is incrementally adjusted (Direction 1 in Figure 3.3). If power increases, the perturbation continues in the same direction; if power decreases, the direction reverses (Direction 2).

Oscillation and Trade-offs: Near MPP, the P&O method inherently oscillates around the optimal point. Reducing the step size minimizes these oscillations but slows tracking response, while larger steps improve speed at the cost of steady-state accuracy [24]

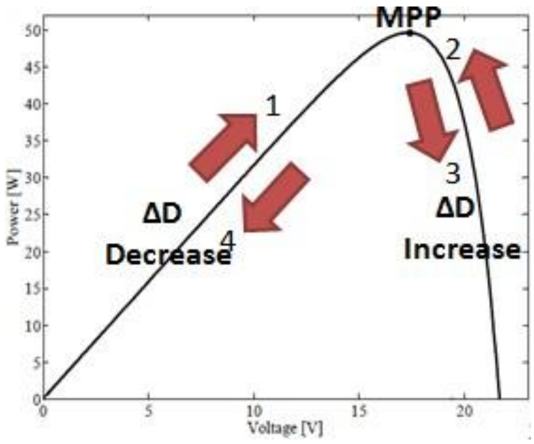

Figure 3.3: Solar power and voltage relation graph

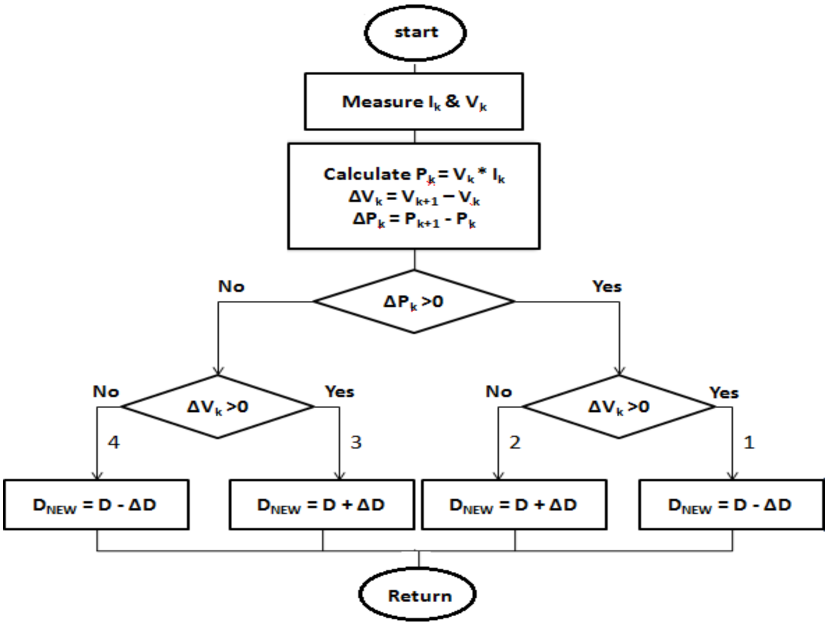

Figure 3.4: P&O strategy

Decision Logic: The algorithm relies on real-time measurements of PV current and voltage. For instance:
1. If ΔP/ΔV>00, the operating point lies on the left of MPP (increase voltage).
2. If ΔP/ΔV<0 the operating point lies right of MPP (decrease voltage).

The step size, dynamically adjusted based on power gradients, is fed to the DC-DC converter to regulate the PV array's operating point (Figure 3.4).

3.2.1 MATLAB Implementation of P&O Strategy

The P&O algorithm is modeled in MATLAB/Simulink, as shown in Figures 3.5 (schematic of the PV system) and 3.6 (subsystem implementation). The simulation framework includes:
PV Array Model: Configured with manufacturer-specified parameters.

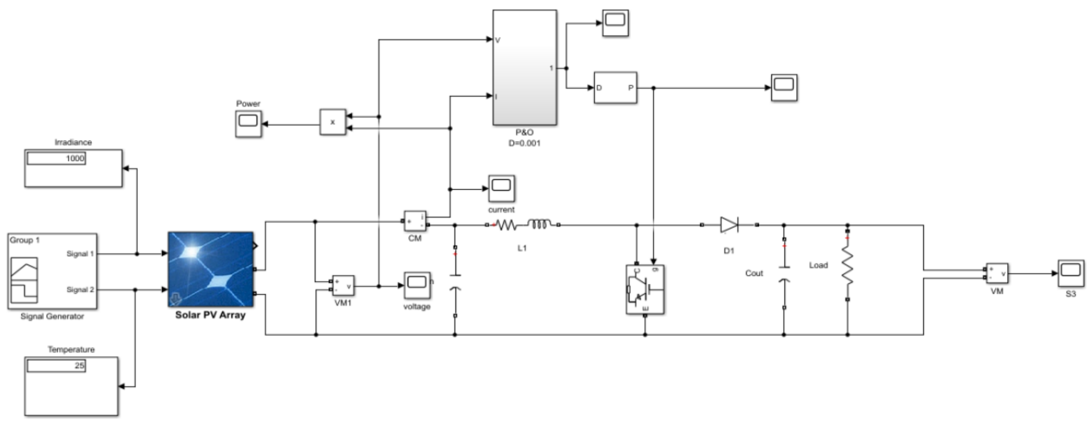

Figure 3.5 - The Smart Solar Navigator: P&O MPPT System Blueprint

DC-DC Converter: Controlled by the P&O logic to adjust duty cycle.
Load Dynamics: Emulates real-world variations to validate MPPT robustness.

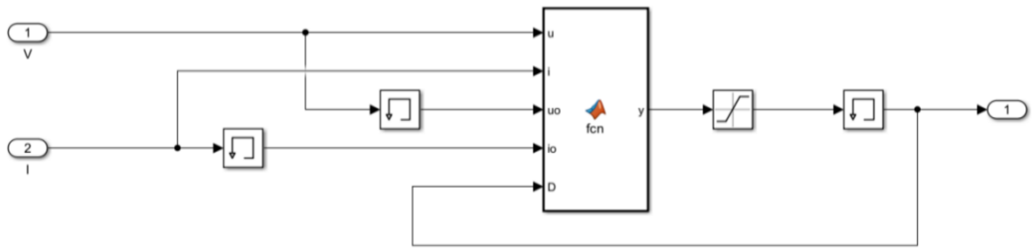

Figure 3.6 – The Brain Behind the Operation: P&O Strategy in MATLAB/Simulink

3.3 Smart Solar Tracking: The Incremental Conductance Method
The slope of the solar system's power-voltage (P-V) curve is critical for achieving the Maximum Power Point (MPP). When the slope reaches zero, the system attains the MPP, while a negative slope indicates operation on the left side of the MPP and a positive slope corresponds to the right side [25]. The MPP is located by comparing the incremental conductance (dIdV) with the instantaneous conductance (IV). This comparison determines the reference voltage (Vref), which corresponds to the MPP voltage (VMPP) the optimal operating point for maximum power extraction.
Any variation in solar irradiance or temperature alters the current-voltage (I-V) characteristics, disrupting MPP tracking. To mitigate this, the tracking speed and stability must be balanced:

A larger incremental step size accelerates MPP convergence but introduces oscillations.
A smaller step size improves steady-state accuracy but slows tracking.

To optimize performance, a two-stage approach is adopted:
1. Coarse Tracking: The operating point is rapidly brought near the MPP
2. Fine Tracking: The IC strategy refines the MPP location with high precision.

His method enhances the dynamic response while minimizing oscillations, as mathematically expressed below.
The mathematical rules are as follows:

At perfect power: $dI/dV = -I/V$ (Equation 3.2)
If we are left of the peak: $dI/dV > -I/V$ (Equation 3.3)

If we are right of the peak: $dI/dV < -I/V$ (Equation 3.4)

To ensure the error signal (E) in Equation (3.1) converges to zero, a Proportional-Integral (PI) controller is employed. The system utilizes two sensors:
1. A voltage sensor measures PV array output.
2. A current sensor to monitor load current.

A Digital Signal Processor (DSP) or microcontroller processes these measurements, maintaining a historical record of voltage and current data. This enables real-time adjustments to sustain operation at the MPP [26], as illustrated in Figure 3.5

3.3.1 Bringing the IC Algorithm to Life: System Blueprint
Figure 3.7 shows the complete "nervous system" of our smart solar tracker, built in MATLAB/Simulink. This is not just a diagram – it is the digital twin of how the Incremental Conductance algorithm talks to the solar panels and power electronics in real-time

3.3.2 MATLAB Subsystem for Incremental Conductance Controller
The IC algorithm's subsystem, modeled in MATLAB/Simulink, is presented in Figure 3.8. This block diagram highlights the logic for slope calculation, reference voltage generation, and PI-based duty cycle adjustment.

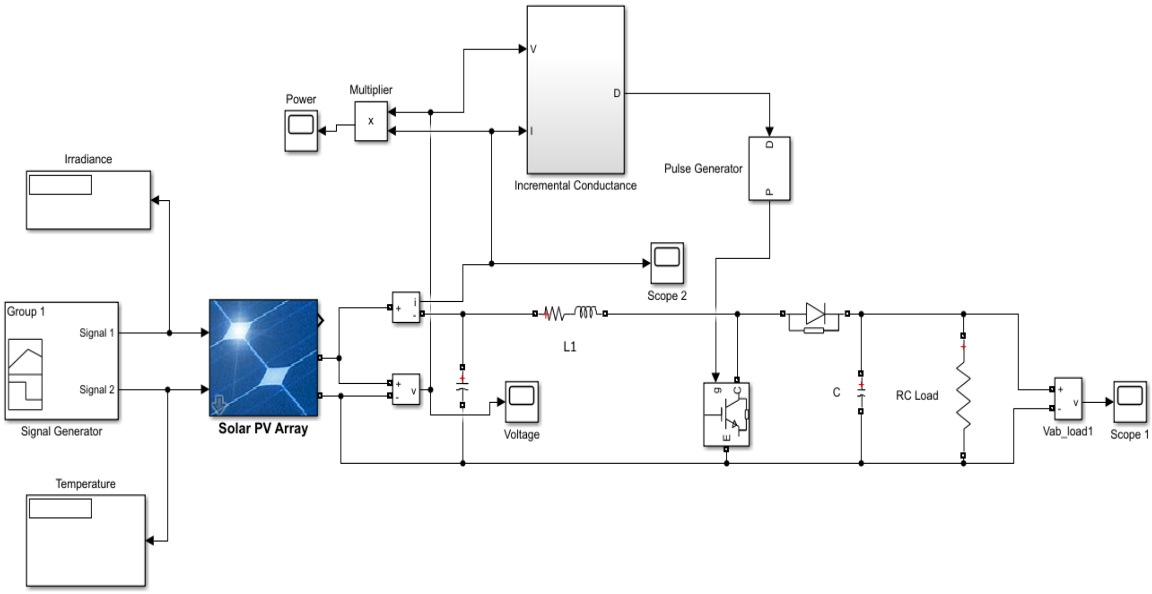

Figure 3.7: Schematic Diagram of IC Strategy based solar system

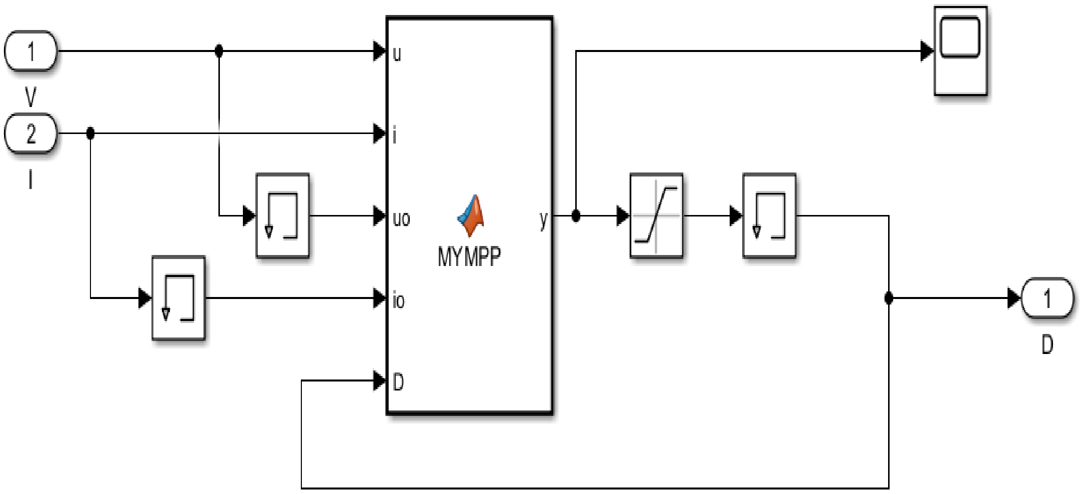

Figure 3.8: Incremental Conductance Controller MATLAB Subsystem

3.4 Fuzzy Logic Controller
Overview of Fuzzy Logic in MPPT

Fuzzy Logic Control (FLC) has emerged as a robust alternative to conventional MPPT techniques, offering superior tracking efficiency without requiring precise system modeling. Its inherent tolerance to input uncertainties and nonlinearities makes it particularly suitable for PV systems operating under dynamic environmental conditions [27].

FLC Operational Stages

The FLC process comprises three stages, illustrated in **Figure 3.9**:

Fuzzification: Crisp inputs (error E and change in error ΔE) are mapped to linguistic variables (e.g., Negative Big, Zero) using membership functions (Figure 3.10).

Rule Evaluation: A rule base (Table 3.1) correlates input combinations to output actions (duty cycle adjustments).
Defuzzification: Linguistic outputs are converted back to numerical values for PWM control

Equations for Input Variables:

$$EN = \frac{P(n)-P(n-1)}{V(n)-V(n-1)} \qquad (3.5)$$

$$\text{Change in Error signal } (\Delta E\ (n)) = \text{ Error signal } (E(n)) - E(n-1) (3.6)$$

where E(n)is the instantaneous error, and P(n), V(n)denote power and voltage at time step *n* [30].

Membership Functions and Rule Base
Figure 3.10 shows a 7-level fuzzification scheme (NB, NM, NS, ZE, PS, PM, PB) for high precision.
Table 3.1 defines the rule matrix linking E and ΔE to duty cycle changes.
Example: If E is Positive Big and ΔE is Negative Small, the output is Positive Medium.

Duty Cycle Adjustment
The controller dynamically adjusts the duty cycle to drive E→0 ensuring operation at the MPP. Deviations from the MPP trigger corrective actions via the rule base [31]–[32].

Implementation Variants
While Mamdani's method (most common) is used here, alternatives like Sugeno or Larsen offer trade-offs in computational efficiency [33].

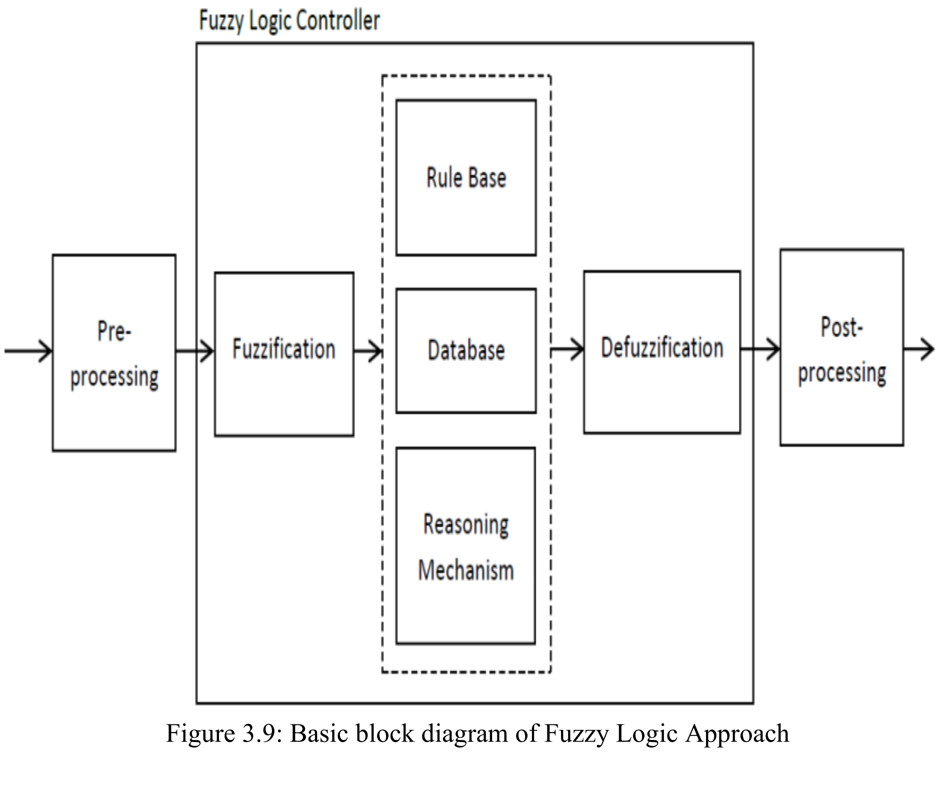

Figure 3.9: Basic block diagram of Fuzzy Logic Approach

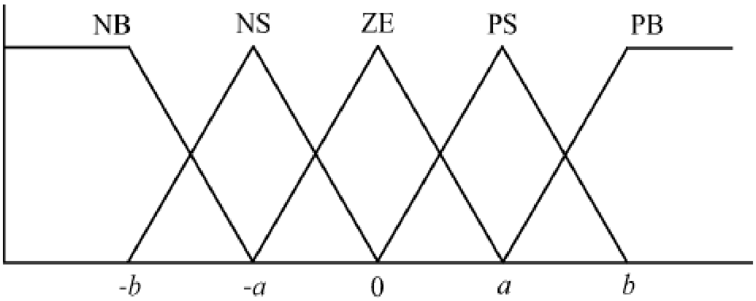

Figure 3.10: Membership function during fuzzification

Current Power Deviation Trend ⬇	Way Too Low (Neg. Big)	Too Low (Neg. Medium)	Slightly Low (Neg. Small)l	Perfect (Zero)	Slightly High (Pos. Small)	Too High (Pos. Medium)	Way Too High (Pos. Big)
Plummeting	MAX BOOST	MAX BOOST	MAX BOOST	MAX BOOST	Moderate Boost	Small Boost	Hold
Falling	MAX BOOST	MAX BOOST	Moderate Boost	Moderate Boost	Small Boost	Hold	Small Cut
Slightly Falling	MAX BOOST	Moderate Boost	Small Boost	Small Boost	Hold	Small Cut	Moderate Cut
Stable	MAX BOOST	Moderate Boost	Small Boost	Hold	Small Cut	Moderate Cut	MAX CUT
Slightly Rising	Moderate Boost	Small Boost l	Hold	Small Cut	Small Cut	Moderate Cut	MAX CUT
Rising	Small Boost	Hold	Small Cut	Moderate Cut	Moderate Cut	MAX CUT	MAX CUT
Skyrocketing	Hold	Small Cut	Moderate Cut	MAX CUT	MAX CUT	MAX CUT	MAX CUT

Table 3.1: Smart Solar Adjustment Rules

3.4.1 Schematic Diagram of FLC-Based Solar System

Figure 3.11 presents the MATLAB/Simulink model of the FLC-controlled PV system, integrating fuzzification, rule evaluation, and PWM generation

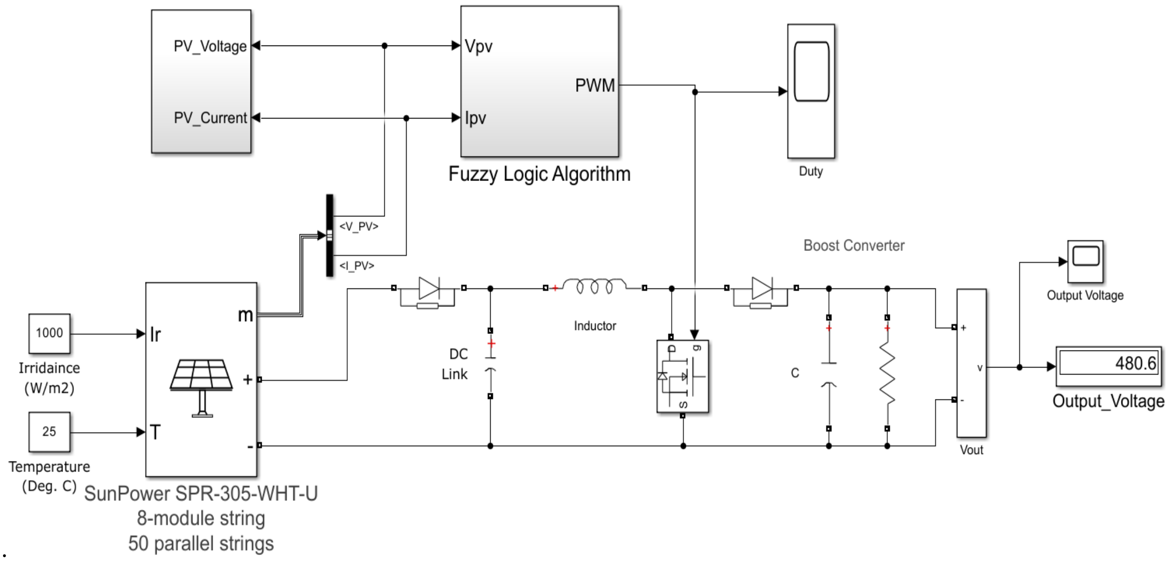

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Figure 3.11Bringing Solar Systems to Life with MATLAB Simulink

3.4.2 FLC MATLAB Subsystem

The subsystem (Figure 3.12) details the fuzzification block processing E and ΔE signal

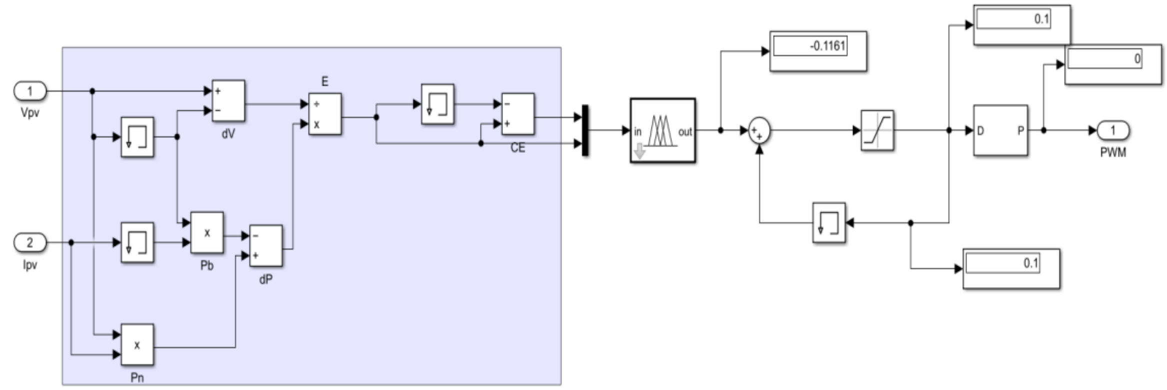


Figure 3.12: FLC MATLAB Simulink Subsystem

3.5 Modeling the Solar PV Array

3.5.1 Fundamental Principles

Solar cells utilize semiconductor p-n junctions to convert sunlight into electrical energy via the photovoltaic effect. When photons with energy exceeding the material's bandgap (Eg) strike the cell, electron-hole pairs are generated, producing a photocurrent (Iph) proportional to solar irradiance [34].1

The single-diode model (Figure 3.13) represents a solar cell’s electrical behavior, comprising:

1. Current source: Photocurrent (Iph)
2. Parallel diode: Accounts for recombination losses (Io, ideality factor N)
3. Resistances: Series (Rse) and shunt (Rsh) resistances model parasitic losses

3.5.2 Mathematical Modelling

The current output (Ipv) of a solar cell is given by:

$$Ipv = Iph - Io(e^{\frac{q(Vpv+IpvRse)}{NKT}} - 1) - \frac{(Vpv+IpvRse)}{Rsh} \quad (3.7)$$

e: Electron charge (1.602×10−19 C1.602×10−19C)
k: Boltzmann constant (1.381×10−23 J/K1.381×10−23J/K)
T: Junction temperature (K)

Photocurrent Calculation:

$$I_l = \frac{\lambda}{\lambda_{ref}}[I_{sc,ref} + \mu_{Isc}(T - T_{ref})] \quad (3.8)$$

where Isc= short-circuit current, Ki= temperature coefficient, G= irradiance.

Reverse Saturation Current:

$$Ir = Ir,ref(\frac{T}{Tref})^{\frac{3}{A}}\exp\,[qEg\,\frac{(\frac{1}{Tref}-\frac{1}{T})}{kA}] \quad (3.9)$$

Simplified Model (neglecting Rsh) for module-level analysis:

$$Ipv = Np * Iph - Np * Io(e^{\frac{q(Vpv+IpvRse)}{NKT*Ns}} - 1) \quad (3.10)$$

3.5.3 Simulation Parameters

The MATLAB model uses SunPower SPR-305W modules (96 cells/module) configured as:
8 modules in series per string
50 parallel strings

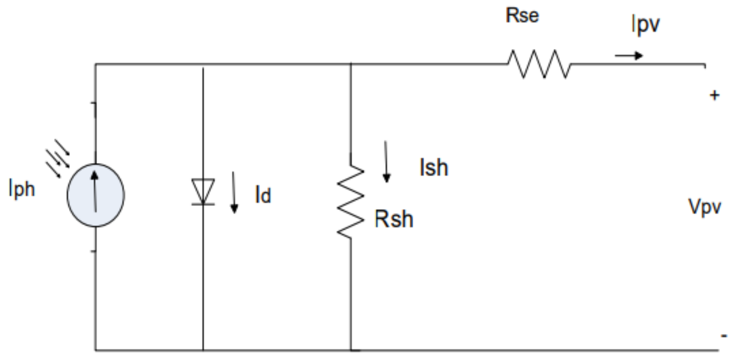


Figure 3.13: Equivalent Circuit diagram of solar energy cell

#	Specification	Value
1.	Panel Model	SunPower SPR-305W
2.	Rated Power per Panel	305W
3.	Solar Cells per Panel	96
4.	Open Circuit Voltage (No Load)	64.2
5.	Optimal Operating Voltage	54.7
6.	Maximum Current (Short Circuit)	5.96
7.	Optimal Operating Current	5.58
8.	Panels per String	8
9.	Total Strings in Array	50
10.	Voltage Drop per °C Rise (Open Circuit)	-0.177 V/°C
11.	Voltage Drop per °C Rise (Operating)	-0.186 V/°C
12.	Current Change per °C Rise (Short Circuit)	0.003516 A/°C
13.	Current Change per °C Rise (Operating)	-0.00212
14.	Diode Performance Level	1.25

Table 3.2: Solar Module Technical Specifications

3.5.4 Characteristic Curves
Figures 3.14–3.15 show simulated P-V and I-V curves under standard test conditions (STC):
Nonlinear P-V curve highlights the MPP at 54.7 V.
I-V curve exhibits exponential diode behavior near Voc.

3.6 Modelling of DC-DC Converter

3.6.1 Converter Fundamentals
Modern photovoltaic systems universally employ DC-DC converters to regulate the variable output of solar arrays. In this work, a boost converter topology has been implemented in MATLAB/Simulink to achieve maximum power point tracking (MPPT). The converter's essential function is to match the PV array's internal impedance with the load impedance through pulse-width modulation (PWM) control l.Inductor is modelled mathematically using equation 3.11:

$$Lmin = \frac{D(1-D)^2 R}{2f} \qquad (3.11)$$

Capacitor is modelled mathematically using 3.12:

$$C = \frac{D}{R(\frac{\Delta Vo}{Vo})f} \qquad (3.12)$$

Where D is the duty of the converter generated by the logic.

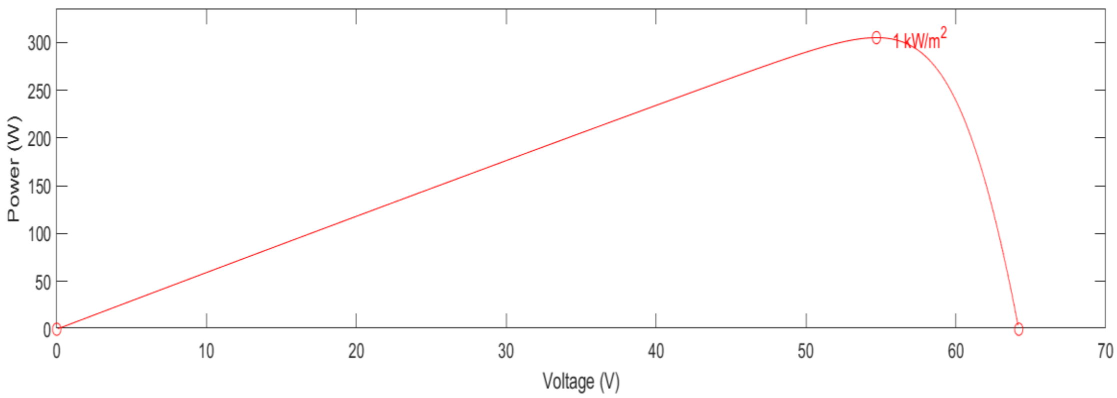


Figure 3.14: Solar Module PV-Curve

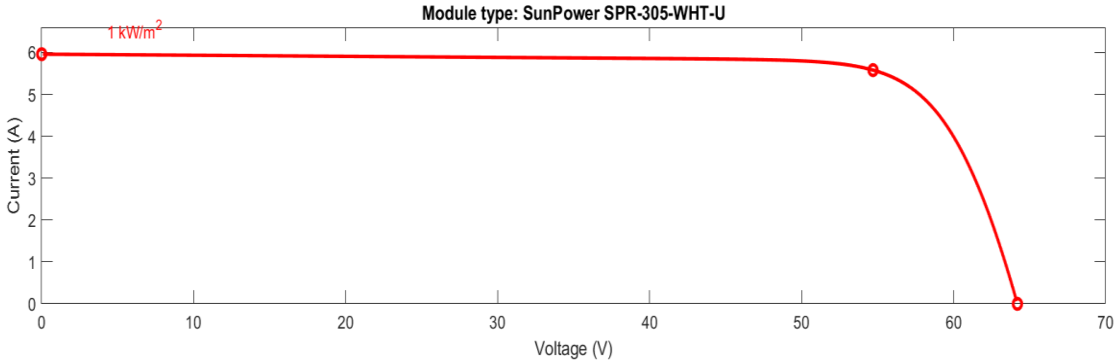
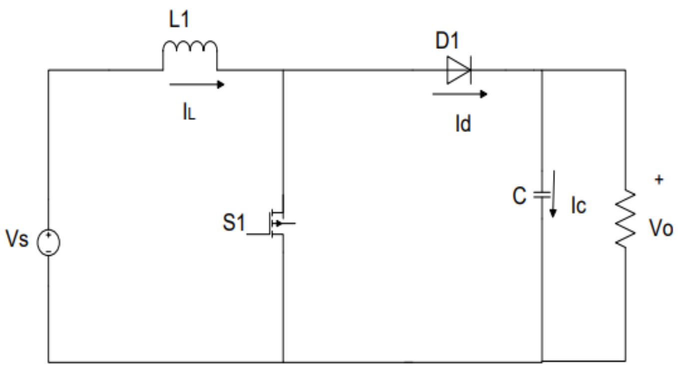


Figure 3.15: Solar Module V-I Curve



You can see the boost converter's circuit design in Figure 3.16. This key component steps up the voltage from our solar panels to match what the grid requires.

Feature	Petrub & Observe	Incremental Conductance	Fuzzy Logic Control
Max Power Output	119.3kW	121.9 kW	121.3kW
Operational Voltage	401.9 V	431.1 A	426.2 V
Current Flow	297A	282.7	285 A
Response Speed	Fastest(0.148)	Slowest(0.37)	Balance(0.2s)
Stability	Minor Vobbles	Noticeable Fluctuation	Rock Steady
Power Surges	Significant	Moderate	None

Table 4.1: Real-world performance of different solar tracking methods

V. Conclusion

5.1 Conclusion

Our research put three leading solar tracking strategies through their paces in a MATLAB Simulink "obstacle course" of changing sunlight conditions. The classic Perturb and Observe (P&O) method proved it is still a dependable workhorse - simple to implement and reasonably accurate, but like an overeager assistant, it tends to overcorrect (creating power oscillations) and reacts clumsily to sudden cloud cover (causing noticeable overshoot). The Incremental Conductance approach emerged as a thoughtful upgrade - demonstrating sharper precision and better adaptation to environmental changes, though it still showed slight "nervous energy" with minor oscillations during transitions. These real-world performance nuances reveal critical engineering tradeoffs: while both conventional methods get the job done, their limitations in dynamic conditions set the stage for evaluating Fuzzy Logic Control's potential as a more sophisticated solution.

In contrast, the Fuzzy Logic Control (FLC) approach proved to be the most robust and adaptive among the three. Simulations confirmed its superior performance, high accuracy, and excellent stability, even under complex solar conditions. Unlike P&O and InC, FLC exhibited no oscillations or overshoot, with a fast response time. The primary limitation of FLC lies in its computational complexity, which may hinder real-time implementation in low-cost systems.

Based on the findings, the selection of an MPPT technique should consider the trade-offs between simplicity, accuracy, dynamic response, and computational demand, depending on the application and environmental conditions.

5.2 Future Work

To further enhance MPPT performance and applicability, future research should explore the following directions

1. Hybrid MPPT Techniques

Combining the strengths of different MPPT methods (e.g., integrating FLC with InC or P&O) could mitigate individual limitations while improving overall efficiency and robustness.

2. Machine Learning-Based MPPT Optimization

Advanced AI techniques, such as neural networks, deep learning, and reinforcement learning, could refine MPPT decision-making processes, enhancing adaptability and tracking precision under rapidly changing conditions

3. Experimental Validation and Commercial Viability

While this study relied on MATLAB simulations, future work should include **real-world experimental testing** to validate results. Additionally, cost-effectiveness and reliability optimizations should be investigated to facilitate commercial adoption.

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