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An Intelligent Hybrid MPPT Strategy Combining Fuzzy Logic and Perturb & Observe Algorithms

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ABSTRACT: This paper investigates methods for enhancing the operational efficiency of photovoltaic systems, particularly given that their maximum power output is sensitive to fluctuations in temperature and solar irradiance. To mitigate this variability, Maximum Power Point Tracking algorithms are routinely utilized. This research evaluates diverse MPPT methodologies and proposes an innovative hybrid strategy that amalgamates the conventional Perturb and Observe (P&O) algorithm with a Fuzzy Logic Controller. This proposed hybrid method seeks to combine the rapid response of a large perturbation step with the stability and minimal oscillation associated with a small perturbation step. A photovoltaic system model, encompassing a solar module and a DC-DC converter was developed and simulated using MATLAB/Simulink. The findings confirm the efficacy of MPPT techniques in extracting maximum power. Significantly, the proposed FLC-P&O method exhibits a notable reduction the oscillation of power around the maximum power point compared to the traditional P&O method, while concurrently maintaining a swift response. The study concludes that this hybrid FLC-P&O method offers superior performance, characterized by rapid convergence and minimal steady-state oscillation.

Keywords: **PV Cell, DC-DC Boost converter, Perturb and Observe algorithm, Fuzzy Logic Controller.**

الملخص: تبحث هذه الورقة في طرق تعزيز الكفاءة التشغيلية لأنظمة الطاقة الكهروضوئية، خاصةً بالنظر إلى أن الحد الأقصى لقدرة إنتاجها يتأثر بتقلبات درجات الحرارة وشدة الإشعاع الشمسي. وللتقليل من هذا التغير يتم استخدام خوارزميات تتبع نقطة القدرة القصوى بشكل روتيني. يقوم هذا البحث بتقييم منهجيات (MPPT) المختلفة ويقترح استراتيجية هجينة مبتكرة تجمع بين خوارزمية "التحوير والملاحظة" التقليدية (P&O) ووحدة تحكم بالمنطق الضبابي. تهدف هذه الطريقة الهجينة المقترحة إلى الجمع بين سرعة الاستجابة الناتجة عن خطوة تحوير كبيرة مع الاستقرار والتذبذب الطفيف المرتبطين بخطوة تحوير صغيرة. تم تطوير نموذج لنظام كهروضوئي يشتمل على وحدة شمسية ومحول تيار مستمر–تيار مستمر، وتمت محاكاته باستخدام برنامج (MATLAB/Simulink) . تؤكد النتائج فعالية تقنيات (MPPT) في استخراج القدرة القصوى. والأهم من ذلك أن الطريقة المقترحة (FLC–P&O) أظهرت انخفاضاً ملحوظاً في تذبذب القدرة حول نقطة القدرة القصوى مقارنة بالطريقة التقليدية (P&O)، مع الحفاظ في الوقت نفسه على سرعة الاستجابة. وتخلص الدراسة إلى أن هذه الطريقة الهجينة (FLC–P&O) توفر أداءً متفوقاً يتميز بسرعة التقارب وانخفاض التذبذب في حالة الاستقرار.

الكلمات المفتاحية: الخلية الكهروضوئية (PV)، محول تيار مستمر– تيار مستمر، خوارزمية الاضطراب والمراقبة، متحكم المنطقي الضبابي.

I. INTRODUCTION

The global energy landscape is experiencing a significant shift. With the relentless depletion of finite fossil fuel reserves projected to be exhausted within decades and their profound contribution to environmental degradation and climate change, the imperative to transition to sustainable energy sources has never been more urgent [1]-[2]-[3]. Solar photovoltaic (PV) systems are one of renewable energy technologies, that are pivotal to this transition, providing a clean, abundant, and globally accessible alternative [1]-[2]-[4]-[6].

A primary obstacle in leveraging solar energy stems from the intrinsic inefficiencies of photovoltaic panels and the unpredictable, stochastic character of their power output. Consequently, the electrical generation of a PV module exhibits a non-linear response and is exceedingly vulnerable to variations in solar irradiance and ambient temperature [2]-[3]-[4]-[8]. To optimize energy extraction from incident solar irradiance, photovoltaic systems necessitate continuous operation at their Maximum Power Point (MPP). This point signifies the unique combination of operating voltage and current at which a solar panel achieves its peak power output under prevailing environmental conditions. [1]-[2]-[5].

The technological framework engineered to identify and sustain this ideal operational juncture is referred to as Maximum Power Point Tracking (MPPT). Among the numerous MPPT methodologies that have been formulated, the Perturb and Observe (P&O) algorithm is indisputably the most prevalent in commercial applications, attributable to its straightforwardness, ease of integration, and cost-effectiveness [2]-[3]-[4]-[5]. Notwithstanding its widespread acceptance, the traditional Perturb and Observe (P&O) technique is afflicted by notable limitations, which encompass enduring fluctuations around the Maximum Power Point (MPP) during steady-state scenarios and an inadequate dynamic response in the context of swiftly varying meteorological conditions, frequently resulting in a decline in power output and suboptimal tracking efficiency [3]-[4]-[5]-[7].

To overcome these limitations, researchers have increasingly turned to intelligent control strategies. Fuzzy Logic Control (FLC) has proven to be a particularly powerful and robust solution for MPPT applications [3]-[4]-[5]-[6]-[7]. Unlike conventional methods, FLC does not require a precise mathematical model of the system. Its strength lies in its ability to handle non-linearity, imprecision, and sudden environmental changes using a rule-based approach that mimics human reasoning [5]-[6]-[9]. This allows for adaptive step sizing, minimizing steady-state oscillations while achieving a faster and more accurate tracking response, even during partial shading conditions where multiple power peaks emerge [2]-[6]-[7]-[9].

Given the critical need to enhance the efficiency and reliability of standalone PV systems, a comparative analysis between these established and intelligent methods is of paramount importance. These papers present a simulation study that navigates these techniques, focusing on the performance of the conventional P&O algorithm against an improved, Fuzzy Logic-enhanced P&O technique. Building upon the foundational work explored in the referenced literature [1]-[9], this study aims to provide a clear, empirical comparison of their tracking efficiency, dynamic response, and oscillation characteristics, ultimately contributing to the development of more effective and intelligent energy harvesting solutions. In this paper reviews one characteristic of MPPT method in a solar PV system and make a comparison between the classic of Perturb and observe (P&O) technique and using this method with intelligent hybrid Fuzzy- P&O. The performance of this proposed controller (intelligent hybrid Fuzzy- P&O) is rigorously and has decent results with that Perturb and observe (P&O) technique, providing a comprehensive evaluation of its efficacy.

II. THE PERTURB AND OBSERVE (P&O) METHOD

The Perturb and Observe methodology is among the most widely recognized and uncomplicated strategies employed to ascertain the Maximum Power Point (MPP) within photovoltaic solar energy systems. This widespread acceptance is attributed to its inherent simplicity, cost-effectiveness, and straightforward implementation [11].

A) How it Works?

Imagine you're trying to find the perfect volume on a radio where the signal is clearest, but you can't see the dial. You turn the knob a little (this is the "perturb" step), and you listen to see if the sound gets clearer or more staticky (this is the "observe" step) [11].

The P&O algorithm does the same thing with a solar panel:

1. It marginally alters (perturbs) the operating voltage of the photovoltaic panel by modulating the duty cycle of the associated DC-DC converter.
2. It subsequently monitors the resultant variation in the output power.
3. Should the power exhibit an increase, it signifies that the perturbation has shifted the operating point nearer to the Maximum Power Point (MPP). Consequently, it persists in perturbing in the same direction.
4. Conversely, if the power demonstrates a decrease, it indicates that the perturbation has displaced the operating point away from the (MPP). Therefore, it reverses its trajectory and perturbs in the opposite direction [11].

By repeating this process continuously, the algorithm constantly hunts for and oscillates around the Maximum Power Point.

B) The Key Drawback

The main trade-off with this method is this inherent oscillation. Once it gets near the MPP, it doesn't stop perfectly on it; instead, it keeps bouncing back and forth around it. This leads to a small but constant loss of power, especially under steady sunlight conditions.

You can think of it like a thermostat that constantly switches the AC on and off to keep the room at 22°C, rather than holding it perfectly steady. The P&O method is simple and effective, but it's always "hunting" for the best spot, which causes those power output ripples [11].

III. BLOCK DIAGRAM OF A PHOTOVOLTAIC SYSTEM

The photovoltaic panel module, the DC-DC boost converter, the Maximum Power Point Tracking (MPPT) controller, and the load intended to be energized collectively constitute the block diagram of an (MPPT) control system designed for the generation of solar electricity. A direct load is interfaced with the DC boost converter, which is energized by the output voltage provided by the solar panel. The input (MPPT) controller acquires voltage and/or current measurements from the panel prior to the application of the (MPPT) algorithm. The block diagram of the system is illustrated in the subsequent Figure (1).

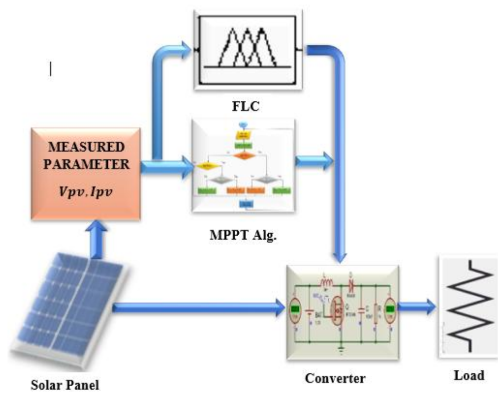


Fig. 1: system's block diagram

A) PV system description

This research employs an independent photovoltaic (PV) system that incorporates a SunPower 1soltech 1STH-215-P (module) solar panel (PV), a DC-DC boost converter, and a resistive load of 313.3991 ohms. The operation of the boost converter is regulated by a pulse width modulation (PWM) signal at a frequency of 5 kHz, which facilitates voltage adjustment to guarantee that the panel functions at its maximum power point (MPP). The system undergoes testing under diverse solar irradiance conditions (ranging from 250 to 1000 W/m²) to assess the efficacy of various maximum power point tracking (MPPT) algorithms. The principal objective is to optimally extract the maximum amount of energy from the solar panel, even in the presence of sudden fluctuations in illumination or load conditions [12].

B) Modeling PV cells

The simplified equivalent circuit of a photovoltaic cell, as depicted in Figure (2), is composed of a single diode representing cell polarization and a parallel current source that models the electric current generated by solar irradiance. To account for intrinsic electrical losses within the photovoltaic cell, two resistors are incorporated into this framework. Specifically, the series resistance Rs models the Ohmic losses occurring at the metal-semiconductor interface and within the front contacts of the photovoltaic cell. On the other hand, the losses in relation to leakage around the cell's edge and metallic contacts are described by the shunt resistance Rsh [13]. The model states that Equation (1) [14]-[10], provides the PV cell's output current:

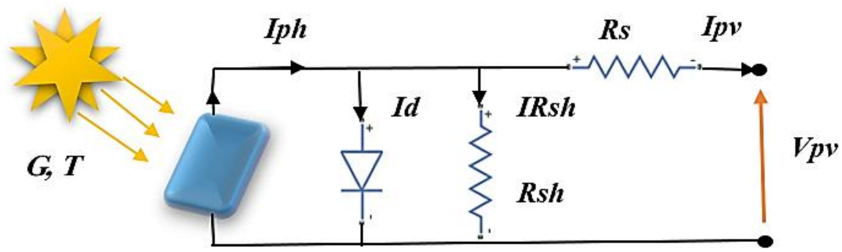


Fig .2: Equivalent circuit of a photovoltaic cell

$$I_{pv} = I_{ph} - I_d - I_{Rsh} \quad (1)$$

$$I_{ph} = \left[I_{ph,ref} + K_i\left(T - T_{ref}\right)\right]\frac{G}{G_{ref}} \quad (2)$$

$$I_d = I_0\left(exp\left(\frac{q(V+IR_S)}{K*n*T}\right) - 1\right) \quad (3)$$

$$I_0 = I_{0,ref}\left(\frac{T}{T_{ref}}\right)^3 exp\left(\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\frac{qE_g}{K*n}\right) \quad (4)$$

$$I_{pv} = I_{ph} - I_0\left(\left(\frac{q(V+IR_S)}{K*n*T}\right) - 1\right) - \frac{V+IR_S}{R_{sh}} \quad (5)$$

Where :

I_{pv}	output current of the cell
I_{ph}	photocurrent
G	incident radiation
T	operating temperature
Ki	temperature coefficient
$I_{ph,ref}$	photocurrent at reference point
T_{ref}	reference T
Id	diode current
q	charge of the electron
K	Boltzmann constant
n	ideality factor
I_0	reverse saturation current

The 1Soltech 1STH-215-P photovoltaic panel provided the requisite parameters employed in this analysis (refer to table 1). It is apparent that the power-voltage (P-V) curve of the photovoltaic array exhibits nonlinearity, thereby complicating the processes of control analysis, design, and modeling. Consequently, it is imperative to sustain the output energy of the photovoltaic array at the maximum power point (MPP). The necessity for maximum power point tracking (MPPT) control, which modulates the output voltage and current of the photovoltaic array through pulse-width modulation (PWM) to attain its MPP, effectively addresses this requirement.

It is indeed practicable to construct characteristic curves for a solar panel by varying the voltage and temperature, subsequently enabling the determination of the corresponding current values through the utilization of the provided equations alongside the data delineated in table (1). The attributes of the solar cell at varying irradiance levels, while maintaining a constant temperature of $25^{\circ}C$, are depicted in Figure (3). Figure (3. a) elucidates the influence of irradiance on the current-voltage (I-V) characteristics, whereas Figure (3.b) presents the energy-voltage (P-V) characteristics, with temperature held constant at $25^{\circ}C$. The data represented in Figure (3) indicates that both current and power outputs exhibit an increase in correlation with elevated radiation levels. Consequently, the output energy is profoundly influenced by the radiation intensity.

Table (1): Specifications of *1Soltech 1STH-215-P* PV Module

Parameter	Value
Maximum Power (w)	213.15
Open circuit voltage Voc (v)	36.3
Voltage at maximum power point Vmp (v)	29
Temperature coefficient of Voc (%/deg.c)	-0.36099
Cells per module (Ncell)	60
Short circuit current Isc (A)	7.84
Current at maximum power point Imp (A)	7.35
Temperature coefficient of Isc (%/deg.c)	0.102

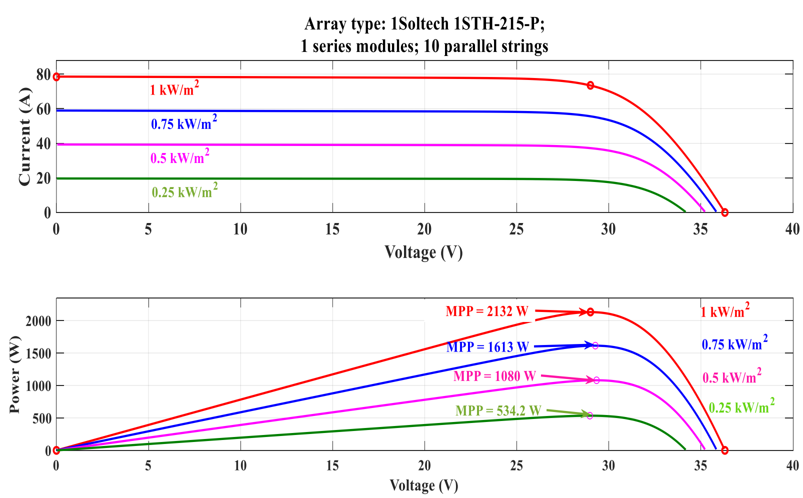


Fig. 3: a), b) I-V and P-V curves at different irradiance levels when T = 25 ◦C

C) DC-DC Boost Converter

The boost converter circuit employed in this simulation represents a fundamental DC-DC power conversion mechanism that elevates the voltage from its input to the output (load) in an asynchronous mode, utilizing a solitary high-frequency switch and a diode. Figure (4) illustrates the schematic representation of the boost converter circuit.

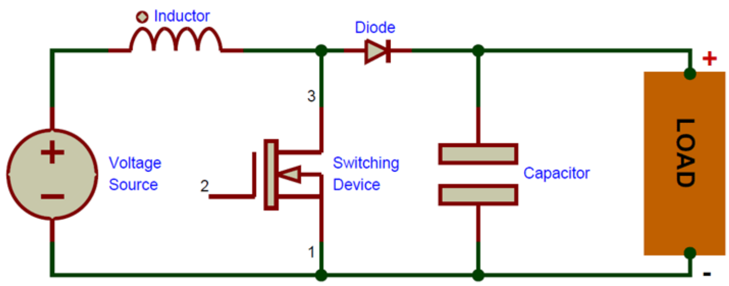


Fig.4: circuit diagram of the boost converter.

Where, the MPPT module generates the command signal and V_{in} is the PV panel's voltage. When the boost converter is configured in continuous conduction mode, its transfer function is:

$$\frac{V_{out}}{V_{in}} = \frac{1}{(1-D)} \tag{6}$$

Where, D is the duty cycle.
In reality, the gate of the power switch (MOSFET) is driven by the command signals from both approaches.

D) The P&O algorithm-based MPPT

This algorithm's primary goal is to maximize power generation from the PV modules; in fact, it acts on the cyclic D ratio and disturbs the PV panel's voltage.
Indeed, the power output generated by the photovoltaic module at time k is influenced by this perturbation and is subsequently evaluated against the preceding measurement at time (k-1). As the power increases, we approach the locus of maximum power (PMP), and the modulation of the duty cycle persists in the same trajectory. Conversely, a decline in power results in a deviation from the (PMP), necessitating a reversal in the duty cycle modulation, and so forth [15].

The following Figure (5) provides the P&O algorithm:

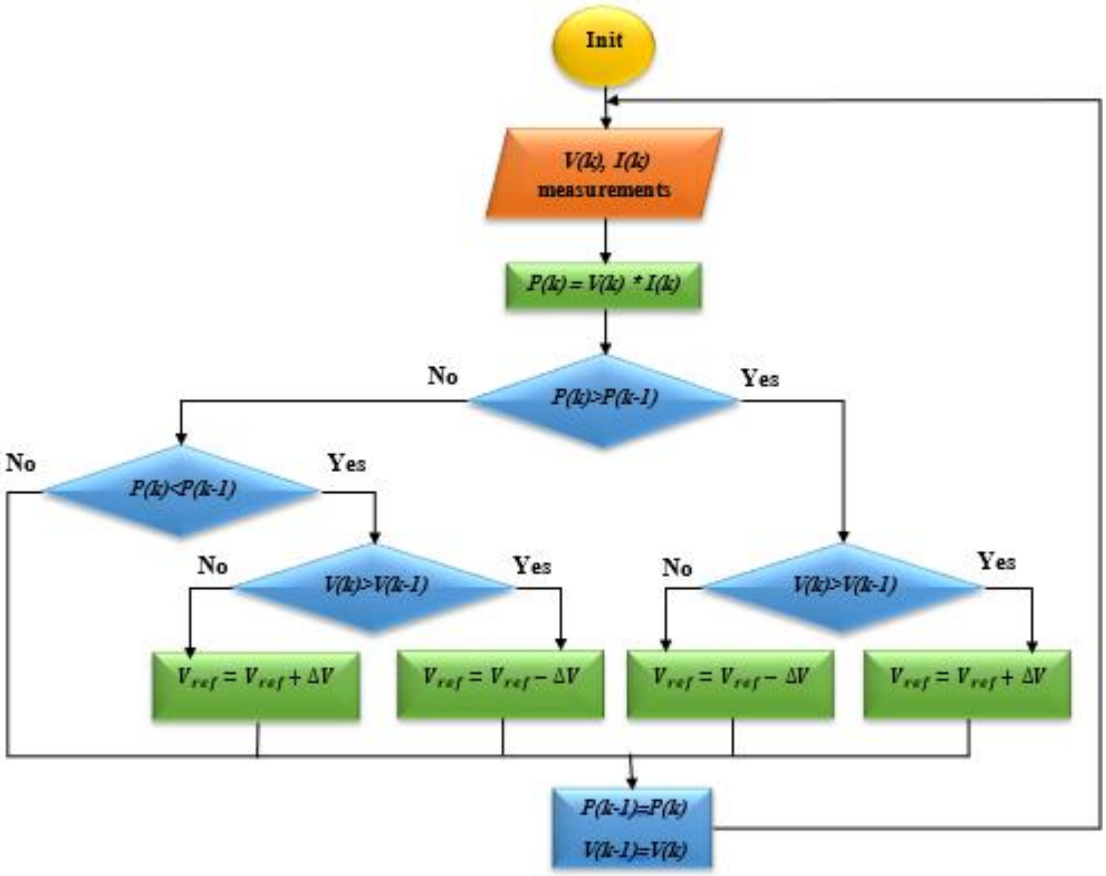


Fig. 5: Perturb and Observe (P&O) algorithm

E) Conventional MPPT Control Algorithm

Are the simple, automatic stands that try to find and hold that perfect spot.

There are two main types: The "Trial and Error" (Perturb & Observe - P&O) and the "Slope Detective" (Incremental Conductance - InC) methods.

F) The "Trial and Error" Method (Perturb & Observe - P&O)

This method is like a person blindly searching for the best signal on a radio.

- *What it does:* It gives the system a small nudge (a "perturbation") and checks if the power got better or worse.
- *The rule:* If the power increased, it keeps nudging in the same direction. If the power decreased, it turns around and nudges in the opposite direction.

- The catch: Once it finds the best spot, it can't stop perfectly still. It constantly overshoots slightly and has to correct itself, causing a tiny, constant wobble around the perfect point, which wastes a little bit of energy [12].
- *Conventional MPPT is a reliable, simple way to find the sweet spot on a solar panel.* The "Trial and Error" (P&O) method is the simplest to build, while the "Slope Detective" (InC) method is a bit more advanced and steadier. Both are widely used because they get the job done without being overly complicated and will use the first method (P&O) to work on this paper.

G) The Fuzzy Logic theory and designing

The fundamental component in the fuzzy logic maximum power point tracking (MPPT) system is the formulation of the Fuzzy Logic Controller (FLC). Typically, the parameters of error (E) and the variation of error (CE) concerning power in relation to voltage or current are frequently utilized as the primary inputs by an FLC. Conversely, certain methodologies implement ΔP and ΔV.

Error (*E*): This can be described as the P-V curve's instantaneous slope $\frac{dP}{dV}$. This slope is zero at the MPP.

$$E(k) = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \quad (7)$$

Change in Error (*CE*): This helps forecast the MPP's direction by showing how the slope changes over time.

$$CE(k) = E(k) - E(K-1) \quad (8)$$

Usually, the FLC's output is the duty cycle change ($\Delta\boldsymbol{D}$), which is then integrated to determine the DC-DC converter's new duty cycle value

H) MATLAB design of fuzzy logic MPPT:

Equations (7) and (8), representing error (E) and change of error (CE), were used to design the fuzzy logic MPPT in MATLAB/Simulink environment. Figure (6) shows how to construct the fuzzy logic MPPT in MATLAB/Simulink environment.

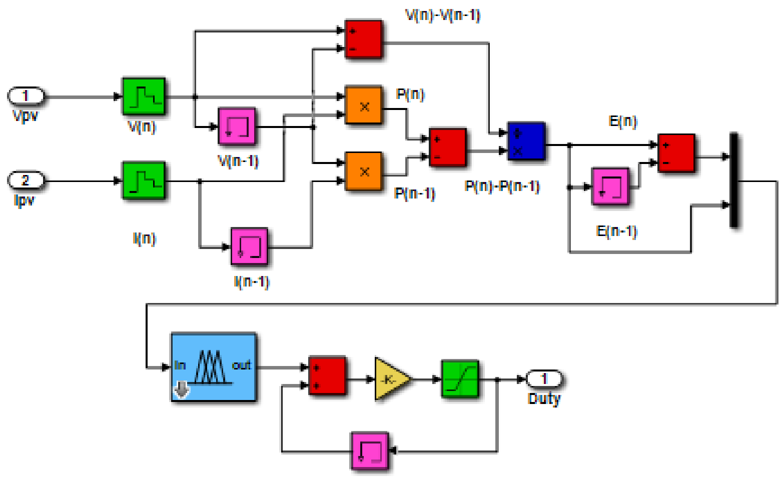


Fig. 6 : fuzzy logic MPPT in MATLAB /Simulink environment

IV. FLC ENGINE

As outlined in the paper, a Fuzzy Logic Controller (FLC) operates through four key steps, mimicking human decision-making:

1. **Fuzzification:** This constitutes the methodology of converting precise, quantitative input data (such as the specific voltage and current measurements obtained from a solar panel) into imprecise linguistic variables. For instance, the "discrepancy" between the current power output and the peak power output may be classified using terminologies such as Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB) through the application of "Membership Functions." These functions, which commonly include Z-shaped membership functions, Gaussian membership functions, and S-shaped membership functions, serve to delineate the extent to which a particular numerical value is associated with each linguistic category [7].
The fuzzy logic diagram used in this paper is shown in Figure (7) below.

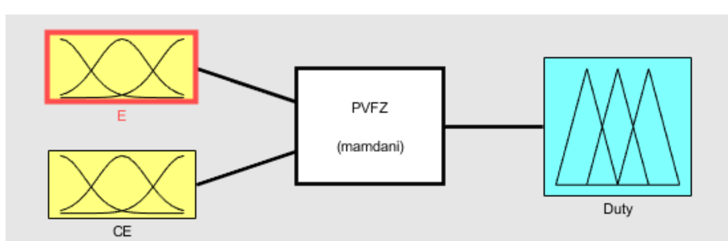


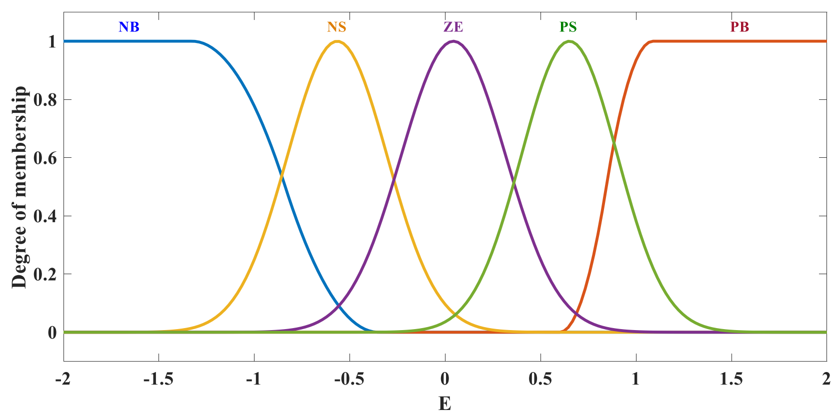
Fig. 7: Fuzzy logic diagram

Two inputs have been examined in this paper:

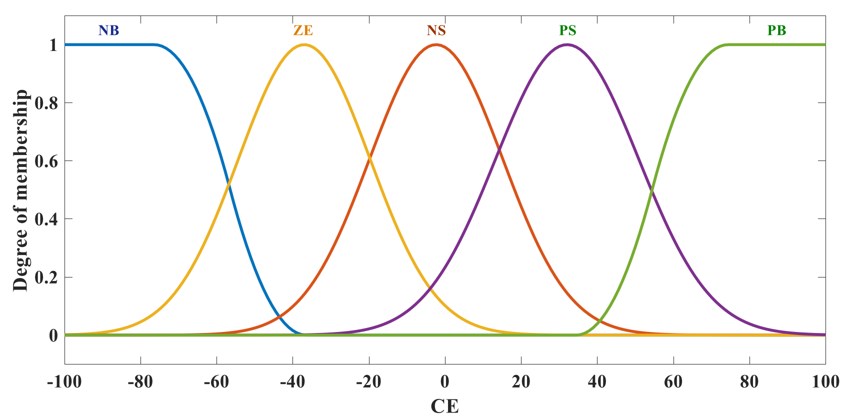
Input 1: $E = \frac{dP}{dV}$, Input 2: $CE = \frac{dE}{dt}$ and one output is the duty cycle change ($\Delta \boldsymbol{D}$).

2. **Fuzzy Inference:** This is the "brain" of the controller. It uses a set of pre-defined "IF-THEN" rules, created from expert knowledge, to make decisions based on the fuzzified inputs. A rule might be: **"IF** the error is Negative Big **AND** the change in error is Zero, **THEN** the change in duty cycle should be Positive Big." The controller evaluates all relevant rules simultaneously to determine a fuzzy output.
3. **Rule Base:** This is the lookup table (2) that contains all the possible "IF-THEN" rules, mapping every combination of input states to an optimal output action.
4. **Defuzzification:** Finally, the fuzzy conclusions from the inference step are converted back into a precise, numerical value that can be used by the system. In this MPPT application, that output is a specific duty cycle signal sent to the DC-DC converter to adjust its operation and push the solar panel toward its Maximum Power Point (MPP). Common methods like the "centroid" method are used for this calculation [7].

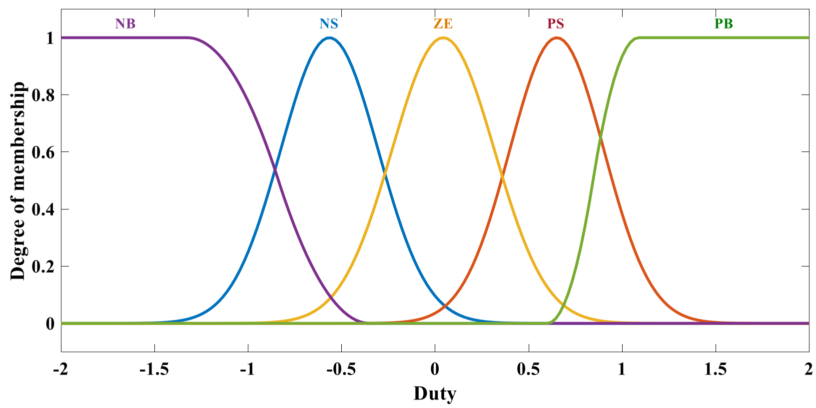
The following Figure (8) a, b and c are the membership function plots:



(a)



(b)



(c)

Fig. 8: a) Membership functions plots for the variable: E, **b)** Membership functions plots for the variable : CE , **c)** Membership functions plots for the variable Duty.

The foundation of the (25) rules established for the fuzzy logic mechanism under consideration is displayed in the following table (2):

Table (2): Rules table

E \ CE	NB	NS	ZE	PS	PB
NB	PB	PB	PS	PB	PB
NS	PB	PS	PS	PS	PB
ZE	NS	NS	ZE	PS	PS
PS	NB	NS	NS	NS	NB
PB	NB	NB	NS	NB	NB

A) Fuzzy Logic Controller (FLC)

Think of the Fuzzy Logic Controller (FLC) as a "smart brain" for a solar panel system. Its main job is to constantly adjust the system to squeeze out the maximum possible power, even as weather conditions like sunlight and temperature change [7].

Instead of using strict "on/off" or "yes/no" logic like a simple thermostat, the FLC thinks more like a human. It uses "fuzzy" terms to make decisions.

Here's how it works in simple steps:

1. It Senses: The controller constantly checks the solar panel's voltage and current.
2. It Calculates "Fuzzy" Errors: It calculates two things:
   - Error (E): How far is the current power from the maximum power?
   - Change in Error (CE): Is the power getting better or worse, and how quickly?
3. It Uses "If-Then" Rules: It runs these numbers through a set of simple, common-sense rules written in plain language. For example:

- "**IF** the error is large and positive **AND** the change is getting worse quickly, **THEN** make a big increase to the power adjustment."
- "**IF** the error is very small **AND** hardly changing, **THEN** just keep the current setting (we're almost perfect)."

4. It Adjusts: Based on these rules, it calculates a new "duty cycle" (the setting that controls the power converter) to nudge the system closer to its maximum power point [7].

- *The advantage* is that this method is very smooth and adaptable. It reduces unnecessary oscillations around the maximum power point, leading to a more stable and efficient system that reacts intelligently to clouds or shading, just like a human operator would.

The FLC doesn't need a complex mathematical model of the solar panel; it just uses practical, intelligent rules to get the best performance.

- *Overview and Modeling of the Fuzzy-P&O Hybrid Technique:*

This section explains the hybrid method that combines the strengths of both the Fuzzy Logic Controller (FLC) and the Perturb and Observe (P&O) algorithms to create a more efficient and robust Maximum Power Point Tracking (MPPT) system.

Overview: Why Combine Fuzzy and P&O?

The core idea behind this hybrid approach is to use the right tool for the right job. Both FLC and P&O have their own advantages and weaknesses:

- *P&O* is simple and effective but has a key flaw: it struggles with fast-changing weather conditions (like a cloud quickly passing over the sun). Its fixed step size causes it to oscillate around the Maximum Power Point (MPP) and it can be slow to catch up when conditions change rapidly.
- *FLC* is excellent at handling non-linear systems and changing conditions intelligently. However, it can be more complex to design and computationally intensive [7].

The hybrid technique proposes a smart switch between these two methods based on what's happening with the sunlight. The system monitors the rate of change in solar irradiance:

- *Slow Changes (e.g., gradual morning to afternoon sun):* The reliable and simple P&O algorithm is sufficient.
- *Fast Changes (e.g., sudden clouds):* The system switches to the FLC, which is better equipped to handle rapid changes intelligently and reduce oscillations.

This way, the system uses the computationally simpler P&O during stable periods and only engages the more powerful FLC when it's truly needed, achieving a perfect balance between performance, stability, and complexity.

B) Modeling:

The mathematical rule to decide when to switch between the two algorithms. The key is to monitor the change in power (ΔP) relative to the previous power value (P).

1. The Threshold: a specific power threshold value of 1 Watt was specified. This value can be adjusted based on the specific solar panel system, but 1W serves as a good benchmark.
2. The Decision-Making Unit: The system constantly checks the change in power between two consecutive moments [7].
    - If the change in power is large ($\Delta P > 1W$)**,** it indicates a fast change in irradiance (like a sudden cloud). The system automatically switches to the FLC algorithm to handle this rapid change quickly and efficiently.
    - If the change in power is small ($\Delta P \leq 1W$)**,** it indicates stable or slowly changing conditions. The system keeps using the P&O algorithm, as it is perfectly adequate for this scenario.

This logic is elegantly simple. The power output of the solar panel itself is used as the sensor to determine how drastically the environment is changing, and the controller chooses the most appropriate strategy in real-time.

The Fuzzy-P&O hybrid isn't just a mix of two algorithms; it's an intelligent manager that assigns tasks based on real-time conditions. It leverages the simplicity of P&O for steady states and the intelligence of FLC for transients, resulting in a system that is both fast-acting and stable, with minimal power oscillation around the maximum power point [7].

V. THE MODEL SIMULATION

Figure (9) illustrates the model of the suggested MPPT based on fuzzy logic control. table (1) lists the specifications of the PV module that was used in this simulation.

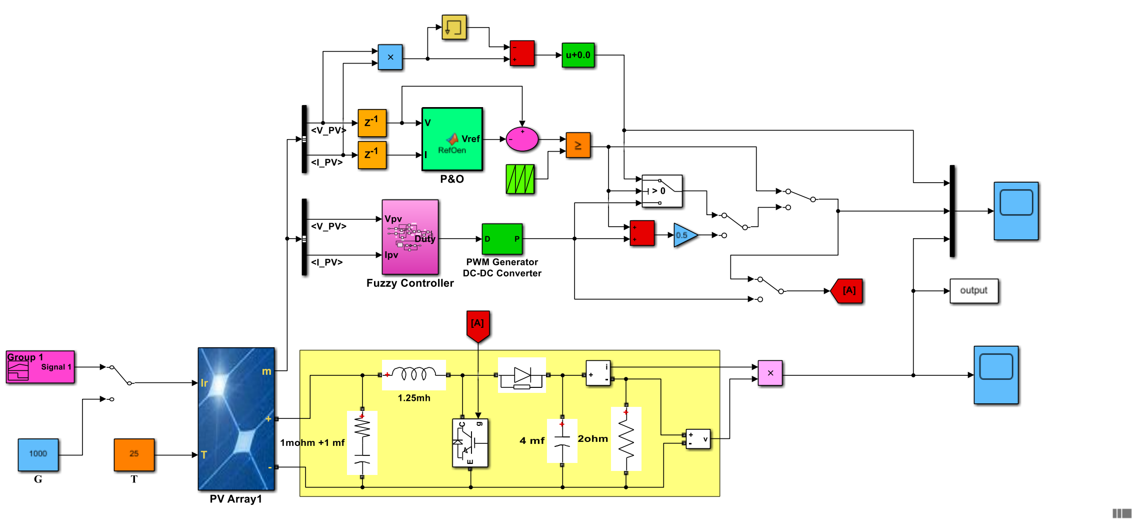


Fig. 9: Suggested MPPT based on fuzzy logic control

VI. SIMULATION OUTCOMES AND DISCUSSION:

The PV Module's results under various irradiation levels, and with constant value of temperature (25^0c) are displayed in the figure below. The performance of the PV system with an intelligent hybrid fuzzy-P&O under various irradiance levels is displayed in Figure (10) a. The irradiance with gradient values are 1000, 750, 500 and 250 W/m^2. In Figure (10) b, illustrates the output of the converter with intelligent hybrid (FLC-P&O) MPPT vs (P&O) MPPT.

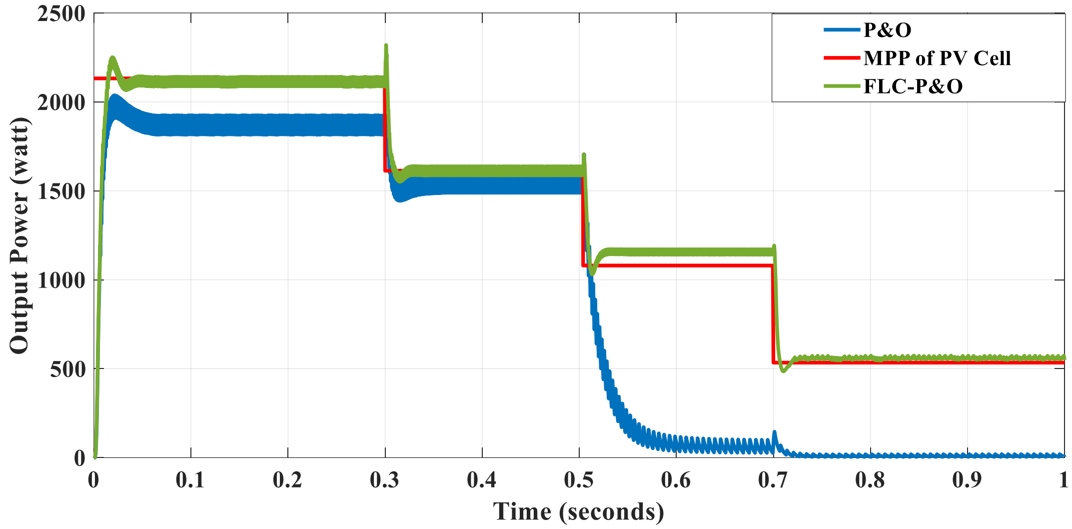


Fig. 10: a) Output Power of Converter

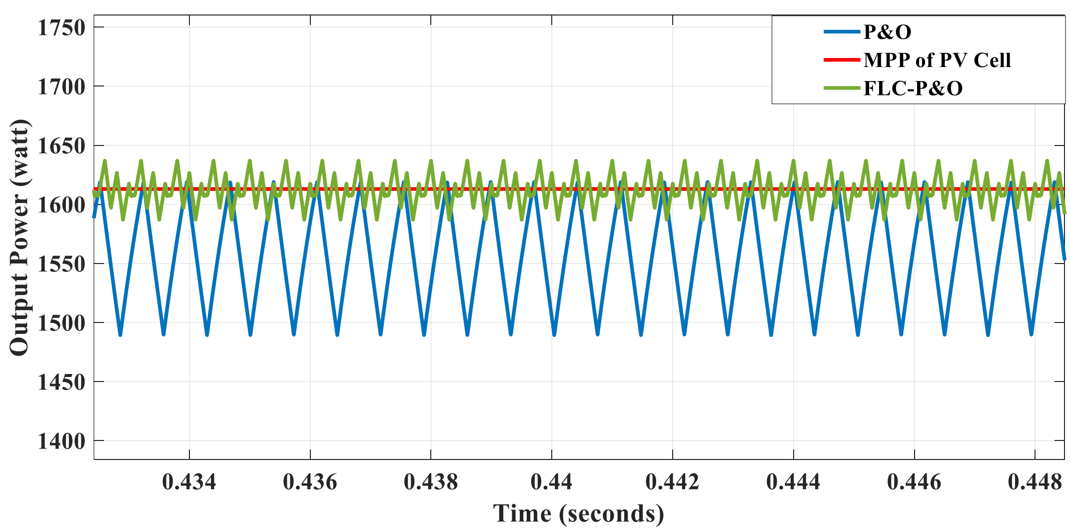


Fig. 10: b) Hybrid (FLC-P&O)MPPT vs P&O MPPT

Figure 10 (a) illustrates the Output Power of the Converter under Different Sunlight Levels. This figure acts like a health check for our solar system under different weather conditions. It shows how much power the system generates when the sunlight intensity (irradiance) changes. The graph shows four distinct "steps" of power. As the sunlight (irradiance) gradation from 1000 W/m² to a 250 W/m², the system's power output gradual. At each new level of irradiance, the system quickly finds a new operating point and stabilizes there. This is a successful test. It proves that the Fuzzy Logic Controller (FLC) is doing its primary job: it's a great "sun tracker." No matter if it's a bit cloudy or fully sunny, the controller successfully hunts down the new "sweet spot" for maximum power and locks onto it. The system is adaptable and responsive to its environment.

Figure 10 (b) presents the Head-to-Head Match-Up (Hybrid FLC-P&O vs. Conventional P&O). This is the main event! This graph compares the performance of our new, smart Hybrid controller against the older, conventional P&O method. The blue line (P&O) constantly jitters and wobbles around the maximum power point. It's like a thermostat that can't quite settle, constantly switching the AC on and off, causing the temperature to oscillate. This constant "hunting" means it's never perfectly at the best point, leading to a small but constant waste of energy. You can see it never holds a steady, smooth line. The green line (Hybrid FLC-P&O) tells a different story. It also reacts quickly to changes, but once it gets close to the maximum power, it settles down with much finer, more precise adjustments. The "jitters" or oscillations are dramatically reduced. It finds the sweet spot and stays there calmly and steadily. The area of the "wobble" around the ideal line represents lost power. The P&O method has a large area of wobble, meaning it loses more power. The Hybrid method has a very small area of wobble, meaning it wastes far less energy. The paper states that hybrid method can cut power oscillation in half, which is a massive improvement in efficiency.

VII. CONCLUSION

A smarter MPPT algorithm is created by merging Fuzzy Logic with the classic P&O method. It delivers the better: the fast response of a large step and the stable precision of a small one, cutting power oscillation in half. Our hybrid FLC-P&O technique solves the classic trade-off in solar tracking. It ensures PV systems react quickly to changing weather while operating with minimal energy waste, significantly boosting efficiency. The standard P&O algorithm is enhanced with Fuzzy Logic to create a superior solar tracker. Consequently, Rapid adaptation to sunlight changes with 50% less power loss, maximizing energy harvest. By intelligently switching between the two strategies based on how rapidly the power is changing, the hybrid system ensures a quick response when needed and calm, efficient operation when possible. This leads to a more stable and efficient solar power system that squeezes every last bit of available energy from the sun.

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