Enhanced P&O MPPT Algorithm Based on Fuzzy Logic for PV System: Brief Review and Experimental Implementation

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Abstract- The maximum power point tracking (MPPT) based perturbation and observation (PandO) approach for photovoltaic (PV) devices is first created in this study after a survey of the literature. The MPPT P&O algorithms described in the state of the art fall into three categories: modifications of the fundamental P&O approach, combinations of P&O techniques with more traditional techniques, and combinations with additional smart techniques. The experimental use of an improved PandO strategy based on fuzzy logic (FL) for PV utilization is then suggested. The traditional P&O method is frequently used in production of solar energy since it is easy to construct and uses inexpensive technology. However, the balance among equilibrium fluctuations and spontaneous reactivity is its fundamental drawback. A FL-based controller block is utilized to offer a variable step in order to address the flaws in current implementations of the classic P&O technique. The results of the experiments demonstrate that the recommended approach's reaction time is faster than the conventional P&O strategy. The efficiency, the average power, the ripple rate of the power and the response time are respectively 99.6%, 100 Watts, 0.05 Watts and 0.01 seconds. These results are interesting regarding the vast majority of similar existing works. Additionally, it is discovered that the stability and energy fluctuations of the suggested control are virtually completely eradicated. Compared to recommended P&O methods accessible in the literary works, the enhanced P&O control based on FL is precise, straightforward, and enables to optimize more quickly for optimal power point.

Keywords P&O, MPPT, fuzzy Logic, photovoltaic devices, experimental results.

1. Introduction

Load shedding and energy shortage issues may now be resolved with photovoltaic (PV) electricity. It has the benefit of not harming the environment and being widely accessible anywhere in the world. Despite technical advances in the production of solar panels used to convert illumination from the sun into electricity, these devices have relatively poor energy conversion efficiency. If the PV array is not used in line with its maximum power point (MPP), its efficiency may be drastically reduced. A crucial step in the planning and implementation of a PV system is monitoring this MPP, which changes location according on the weather. To solve these issues, a maximum power point tracking (MPPT) controller has to be added between the load and the PV generator, allowing the load to be adjusted to the PV generator [1-3].

The literature [2, 4-5] describes a variety of MPPT approaches for solar PV applications and how they are put into practice. Many writers recommend and employ the conventional perturb and observe (P&O) strategy. Table 1 [6-39] provides a breakdown of these changed algorithms into three groups. The authors in reference [11] implement a proposed P&O MPPT process for PV systems. The goal was to address the limits of instabilities brought on by variations in the weather. Their method outperformed the conventional approach's tracking factor by 96% over 90%. To deal with the dynamics surrounding the MPP and steady state changes, the authors in [12] presented the PandO MPPT technique, between 1% and 1.1% more efficient than the HC method, on average. The authors in [13] discuss challenges in tracking the global maximum power point (GMPP) in solar energy systems due to multiple peaks under partial shading, rendering conventional controllers ineffective. To address this, a proposed algorithm incorporates a skipping and scanning mechanism with the perturb and observe algorithm. Their strategy significantly reducing scanning time and demonstrating superior performance in simulations and experiments with an average convergence time of 1.02 seconds and an average efficiency of 99.44%. A novel P&O approach was put out and put to the test in [15] under various irradiance levels. Their approach performs better in terms of tracking speed, tracking precision and dynamic effectiveness. Direct duty cycle control was presented as a hybrid approach by the authors in [29], combining P&O and FOCV. After testing, their solution outperforms the conventional approach by around 15% under uniform illumination and by 25% under partial shadowing. In [30], a brand-new P&O-based ASMC under variable load conditions is proposed. They were able to improve the steady state fluctuation and smooth overflow for unplanned variations in total sun radiation. The Portuguese self-consumer regime in the electricity sector enables medium and low voltage grid customers to be both producers and consumers, enhancing energy efficiency. To optimize solar energy utilization, a modified method incorporating simulated annealing with the conventional PandO algorithm, has been developed in [32] to address partial shading conditions and improve precision in achieving the MPP. In [39], the authors examined the limitations of the P&O algorithm due to issues like convergence speed and steady-state oscillation. It introduces an improved P&O-MPPT algorithm with adaptive FL to enhance convergence speed and stop steady-state oscillation, verified through Matlab/Simulink, demonstrating efficient and accurate tracking of the MPP under varying irradiance levels, outperforming traditional and modified P&O algorithms.

There are numerous goals for this effort. First, a summary of prior research on perturbation and observation MPPT approach for PV consumption is provided, along with a recommendation for a cheap, highly efficient, and moderately priced MPPT algorithm. The creation of a brand-new perturbation and observation MPPT strategy mechanism using FLC with variable step is the other objective.

The study is organized as follows: Section 2 suggests a review analysis of prior research using a modified P&O approach that is comparable. Section 3 emphasizes the PV system setup and solar cell modeling. The traditional P&O method and the strategy for P&O algorithm optimization are both included in Section 4. The experimental results are presented in Section 5, together with an evaluation of the performance of the suggested process and a discussion of some related studies, respectively. The work is completed with a summary that highlights the major ideas.

2. State of the Art of Related Earlier Research

Table 1 presents a classification of the different MPPT algorithms using the P&O method [6-39]. The first subgroup contains authors who have modified the fundamental architecture of the P&O approach. The second sub-group includes works that have combined the perturbation and observation technique with a traditional approach and the last sub-group includes articles that have combined the P&O method with an intelligent method. The first sub-group is used more to increase the accuracy and speed of P&O tracking, as well as the performance of the new approach in a context of fluctuating meteorological factors. The second sub-group offers higher yields than the first. This subgroup also guarantees better PV system performance when load characteristics vary, particularly in shaded conditions. The last category has a very strong ability to predict and anticipate any system difficulties and thus limit losses. It therefore has the best performance, but a complex structure.

3. Photovoltaic Plant Configuration

In this part, we'll describe how to apply the proposed strategy effectively as well as how to use fuzzy logic to optimize the standard MPPT P&O technique.

3.1. Design of the Proposed PV Installation

A synoptic diagram of the experimental PV array configuration is illustrated in Figure 1. A PV array, DS1104 MPPT test equipment, a power converter, a portable computer and an electrical charge are all components of the system. The MPPT technique must take these factors into account since the effectiveness of the solar equipment is temperature-dependent and the sun's radiation are continually changing. This is done by using the power converter boost. Through the DS1104 test board, power moves and equivalents are employed as inputs for the MPPT process. The PC logged into the dSPACE display panel, which is outfitted with the Simulink and Controldesk programs, is in charge of putting the MPPT strategies into practice and starting the PWM signal needed to run the converter.

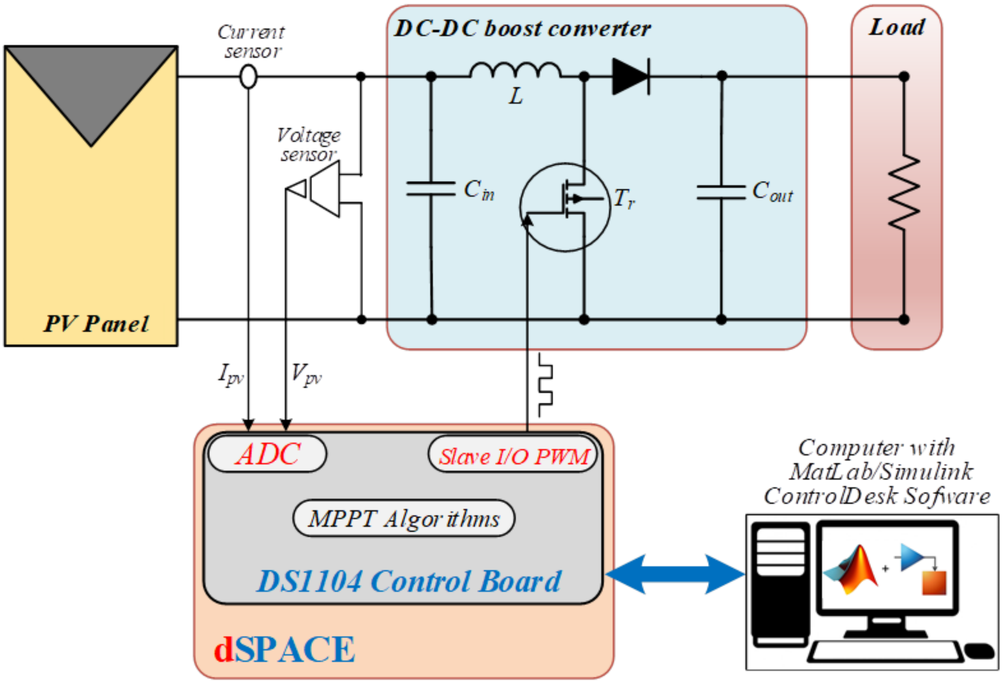

Fig. 1. Schematic diagram of the proposed solar power system.

Table 1. State of the art of the modified P&O MPPT algorithm for photovoltaic devices.

Ref	Strategy for improving the MPPT approaches	Converter used and its application	Simulation Tools	Implementation Tools	Comments
Modified the MPPT Perturb and Observe method's fundamental architecture					
[6]	P&O via Power Threshold Decided (PTD) two step sizes	DC–AC Single-phase full-bridge inverter	Matlab/ S-Function	DS 1103 dSPACE	Deadbeat control is incorporated into the proposed updated P&O scheme to facilitate steady-state functioning at the MPP and faster convergence, which resolves these problems.
[7]	Two modes step sizes P&O	Buck DC-DC converter for autonomous use	PSIM	Microcontroller PIC-16F887	Their cutting-edge P&O addresses the problem of abrupt irradiance and load shifts brought on by partial shade. As a result, they accelerate.
[8]	Drift avoidance (free) P&O	SEPIC DC-DC converter for self-sufficient PV	Matlab/ Simulink	Arduino Atmega 2560 microcontroller	In order to prevent derating, a P&O procedure is proposed that combines along with changes to power and tension, there occurs a change in current. Under rapidly changing climatic circumstances, the suggested technique properly monitors maximum power and prevents derating.
[9]	P&O with variable step-size	Buck DC–DC converter for self-sufficient PV	Matlab/ Simulink	Microcontroller (PIC-16F887)	The goal of the study was to create a modified PandO process for PV arrays that assesses several performance factors while accounting for the DC-DC converter's reaction time.
[10]	PandO by dynamic boundary	DC–DC Buck-Boost converter for self-sufficient PV	Matlab/ Simulink	dSPACE DS1104	In order to decrease prevent losing tracking direction and steady state oscillation, this study suggests a P&O approach for PV devices that dynamically modifies the perturbation size as well as includes a a static limit state.
[11]	Additional loop of calculate load value via PandO	Boost DC–DC converter for sufficient use	Matlab/ Simulink	FRDM-KL25Z development board	The authors updated the P&O scheme for PV devices to address the issue of limiting instabilities brought on by changes in the weather.
[12]	Dynamically after the perturbation step with P&O	Boost DC–DC converter for self-sufficient use	Matlab/ Simulink	NA	In order to dealing with steady-state fluctuations and movements surrounding the MPP, the authors presented an enhanced P&O approach. Between 1% and 1.1% more efficient on average than the HC method.
[13]	PandO with Enhanced Skipping Feature	Buck-Boost converter for self-sufficient PV	Matlab/ Simulink	dSPACE Control Unit	The authors present a novel approach to solar energy optimization that combines a PandO algorithm with a skipping and scanning mechanism. This method reduces scanning time and increases efficiency by constricting the scanning zone. Experimental results

					demonstrate that it performs better than alternative algorithms.
[14]	PandO with adding a third parameter	Boost DC–DC converter for self-sufficient PV	Matlab/ Simulink	NA	In order to address the two primary issues with the standard PandO procedure used in PV devices, this study suggests a revised PandO procedure. This approach speeds up optimization by improving efficiency by an average of 4% under varying isolation settings without adding any more hardware elements.
[15]	Additional irradiance loop P&O	Boost DC–DC converter for self-sufficient use	Matlab/ Simulink	NA (Not Available)	The performance of the traditional PandO approach in tracking the MPP under abrupt and rapidly changing the sun's radiation is examined in this work. The PandO-based-MPP tracking process has been changed by the authors to perform better in terms of tracking accuracy, speed, and efficiency.
[16]	PandO via the perturbation size (*dV*)	Boost DC-DC converter for self-sufficient use	Matlab/ Simulink	NA	This research suggests a new PandO approach for MPPT in PV systems that may extract maximum power even under fast or progressive variations in sun radiation by adaptively determining direction to boost convergence speed, the perturbation size and minimize oscillations.
[17]	PandO via Modified Variable Step-Size (MVSS)	Forward DC–DC converter for self-sufficient PV	Matlab/ Simulink	dsPIC30F2010 microcontroller	The research suggests an MVSS P&O process, which improves transferred available power and addresses various flaws and limitations of the prior MPPT procedure. It has been shown to have advantages in low overshoot, terms of low ripple, and low reaction time.
[18]	PandO via Simplified Model-based State Estimation (SMSE)	Boost DC–DC converter for self-sufficient use	NA	MCU dsPIC33FJ16GS502	The paper suggests a novel MPPT method that outperforms the traditional and variable step-size P&O method in terms of monitoring accuracy, monitoring energy loss, and monitoring time. This method combines SMSE with the adaptive alpha (α-PandO) procedure.
[19]	P&O by Confined search spaced	Boost DC–DC converter for sufficient use	Matlab/ Simulink	Arduino Uno	In order to increase the effectiveness of standalone solar PV devices, the article suggests a solar tracker and suggested PandO scheme. The procedure limits the search space of the power graph to a 10% area that contains the MPP and starts PandO within that space, reducing steady-state oscillations.
[20]	PandO via modified variable Step-Size (MSS)	Boost DC-DC converter for self-sufficient PV	Matlab/ Simulink	Arduino Due	The MSS PandO procedure is confirmed in a material device as efficient with minimal wobbling and rapid pursuit speed. The upgraded algorithms outperform traditional algorithms in terms of the balance state, the duration, and the performance of the inverter.
[21]	Model reference adaptive control (MRAC) by PandO	Boost DC–DC converter, Three-phase grid-integration mode grid-connected	Matlab/ Simulink	OPAL-RT simulator (OP-4510)	In order to provide effective and quicker MPP tracking under varying sunlight and temperature circumstances, this work offers a robust MRAC for MPPT in PV devices integrated. It conducts research on various transport modes and evaluates them in light of current methodology.
[22]	Improved drift-free P&O	Quadratic Boost converter for stand-alone PEMFC	Matlab/ Simulink	NA	The paper suggests a drift-free MPPT method that uses information about recent changes in addition to electricity and voltage change information to increase energy harvesting capability for fuel cells under dynamic settings.
[23]	P&O by model reference adaptive control (MRAC)	Boost DC–DC converter for autonomous PV	Matlab/ Simulink	NA	The recommended controller features a straightforward design, improved dynamic responsiveness, rapid convergence, good efficiency, and minimal oscillations close to the MPP.
[24]	P&O by the variable pitch adaptive (Ad-P&O)	Boost DC–DC converter for autonomous PV	NA	Database collection	The Ad-P&O approach is contrasted to the InC technique, and the results show that the Ad-P&O control outperforms the InC with performance improvements of 99.49% and 80.6% in March and August, respectively, based on a validation with true facts from a PV station in a tropical area.
[25]	P&O by control the duty-cycle perturbation	Boost DC–DC converter for	Matlab/ Simulink	dSPACE DS1104 card	This paper discusses a modified P&O algorithm, addressing issues such as tracking convergence speed,

	step size	autonomous PV			steady-state oscillation, and drift problems, resulting in improved performance under various weather conditions with a 50% reduction in tracking time and a 99.8% steady-state efficiency.
[26]	P&O with variable step-size	Boost DC–DC converter for autonomous PV	Matlab/ Simulink	LPC1768 MCU	The study presents a modified P&O approach that improves efficiency by 98.54% in simulations and real-world trials by using the current direction during irradiance changes, integrating a variable step size, and averaging duty cycle values.
[27]	P&O by estimated open-circuit voltage	Boost DC–DC converter and grid-side inverter (GSI)	Matlab/ Simulink	NA	This paper describes a modified PandO process for solar PV systems that improves efficiency by focusing on a specific region of the power-voltage curve and outperforms current strategies in terms of convergence speed (15ms) and tracking efficiency (99.8%).
Incorporated the traditional PandO approach with one or more traditional MPPT approaches					
[28]	P&O with Fractional Short Circuit Current (FSCC)	DC–DC Boost converter for autonomous use	Matlab/ Simulink	dSPACE DS1104 card	The authors present experimental findings that demonstrate the efficiency of the suggested method and demonstrate its capacity to track the MPP under various operating circumstances.
[29]	P&O with Fractional Open circuit voltage (FOCV)	DC–DC Boost converter for autonomous PV	NA	The ATmega328 microcontroller	In their hybrid solution, the authors combined P&O and FOCV to provide direct duty cycle control. After testing, their solution outperforms the conventional approach by around 15% under uniform illumination and by 25% under partial shadowing.
[30]	P&O with Adaptive Sliding Mode Control (ASMC)	DC–DC Boost converter for autonomous use	Matlab/ Simulink	NA (Not Available)	The control approach, which is based on P&O, estimates the system states using SMC. The suggested approach aims to guarantee the PV arrays' reliable and effective performance under various load scenarios.
[31]	P&O with Incremental Conductance (InC)	DC–DC Boost converter for autonomous use	Matlab/ Simulink	NA	The fundamental idea behind this method is based on automatic variable-size steps that are carried out according to the MPP. When power increases, the method requires significant and high steps; however, when power approaches the MPP, the size of the step is noticeably reduced.
[32]	P&O using a Simulated Annealing (SA)	Boost converter and Single-phase DC-AC inverter	Matlab/ Simulink	Microlabbox with dSPACE	The Portuguese self-consumer regime enables medium and low voltage grid customers to be producers/consumers, contributing to energy efficiency; a study introduces a modified MPPT algorithm using P&O and simulated annealing to address partial shading issues and improve precision in harnessing the MPP for PV cells.
Combined the traditional PandO approach with one or more smart MPPT techniques					
[3]	P&O with Colony Optimization (ACO)	Boost DC–DC converter for standalone	NA	PIC16F876A Digital Controller	Their new strategy, which combines P&O with an ant colony, is a hybrid one. It enhances the GMPP convergence properties for statics and dynamics.
[34]	PandO via Grey Wolf Optimization (GWO)	Boost DC–DC converter for autonomous use	Matlab/ Simulink	dSPACE 1104	Through the GWO, the tracking is done initially. At the very end, the PandO process is computed. The suggested solution offers improved tracking capabilities.
[35]	P&O with Fuzzy Logic (FL)	Boost DC–DC converter for autonomous PV	Matlab/ Simulink	dSPACE DS 1104 board	To minimize processing requirements, authors designed a modified PandO in a FL controller with a minimal rule. Their method has strong dynamic performance in a variety of settings.
[36]	P&O with Artifcial Neural Network (ANN)	Boost DC–DC converter for autonomous use	Matlab/ Simulink	NA (Not Available)	Artificial neural networks and P&O are combined by the authors. P&O seek the MPP in the region where ANN predicts the MPP. The method results in higher PV array power output levels.
[37]	P&O with Fuzzy Logic (FL)	Boost DC–DC converter for autonomous PV	Matlab/ Simulink	dSPACE DS4002 board	The authors discuss the benefits of FL in MPPT, including its capacity to deal with incomplete information and nonlinearity.
[38]	P&O with Butterfly Particle Swarm Optimization (BPSO)	Boost DC–DC converter for autonomous use	Matlab/ Simulink	Arduino Uno Rev3 board	The BPSO and P&O procedures are combined in the suggested process to increase MPPT's accuracy and convergence speed. The initial measurement of the duty cycle is discovered using the BPSO method, and the MPP is tracked using the P&O algorithm.

[39]	P&O by adaptive duty cycle perturbation step fuzzy logic (FL-ΔD)	Boost DC–DC converter for autonomous PV	Matlab/ Simulink	NA	This paper introduces an enhanced PandO algorithm, incorporating adaptive duty cycle perturbation step FL for improved convergence speed and a strategy to eliminate steady-state oscillation, demonstrating superior performance compared to traditional and modified P&O algorithms in tracking MPP under varying irradiance conditions.
this study	P&O by Fuzzy Logic (FL) with a variable step	Boost DC–DC converter for autonomous PV	Matlab/ Simulink	dSPACE DS 1104 board	To decrease computing requirements, authors devised a modified PandO using FLC with a variable step controller and minimal rule. Their method has strong dynamic performance in a variety of settings.

3.2. Solar Cell Modeling

The solar cells are the fundamental component of a photovoltaic (PV) generator, and their mathematical model is created by first identifying its equivalent electrical circuit. Numerous designs, including the two-diode model, the one-diode model, the ideal model, the three-diode model and the model that may be produced by multi-dimensional diodes, are published in the literary works and tested under various circumstances [3, 15, 20]. The above representations were created to depict the semiconductor junction's very nonlinear behavior in the presence of temperature and sun radiation variations. Next, it can replicate how PV behaves in harsh environments like semi-arid or dry regions. A solar cell is an electrical circuit that uses the photovoltaic effect to produce electricity when photons shine on it. The matching single diode model of a solar cell is shown in Figure 2.

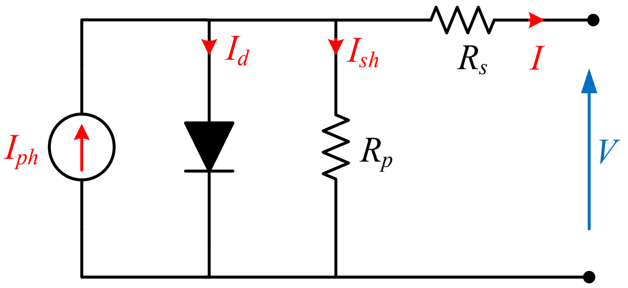

Fig. 2. Single diode solar cells electrical layout.

The current produced by the solar cell is described by equation (1) [12, 19], which is obtained by applying Kirchhoff's principles to the electric circuit of Figure 2.

$$I=I_{ph}-I_O\left[\exp\left(\frac{V+R_S I}{nN_{sc}V_t}\right)-1\right]-\frac{V+R_S I}{R_p}, \quad (1)$$

where the PV cell's output voltage across it and the current flowing through it are denoted, respectively, by I and V. I_{ph} and I_o are reported the diode's inverse saturation current and photo-generated current respectively. n is the ideality factor of the diode.

Equation (2) provides the value of the thermal voltage.

$$V_t=\frac{kT}{q}, \quad (2)$$

where k and q explained the Boltzmann constant and charge of the electron respectively. T is the temperature of the cell.

The photo-generated current is defined by the connection listed below:

$$I_{ph}=\frac{G}{G_{ref}}\left[I_{sc}+K_i\left(T-T_{ref}\right)\right], \quad (3)$$

where G is the sunlight on the PV surface and G_{ref} is the nominal radiation. I_{sc} is the current of the solar cell's circuitry under standard test conditions (STC), which are: 1000 W/m² and 25 °C. K_i is the current coefficient. T and T_{ref} explained to as the actual and benchmark temperatures respectively.

The backwards peak current of a diode is described as:

$$I_O=\frac{I_{sc}+K_i\left(T-T_{ref}\right)}{\exp\left[\frac{V_{oc}+K_v\left(T-T_{ref}\right)}{nN_{sc}V_T}\right]-1}, \quad (4)$$

where K_v and V_{oc} denote the voltage coefficient and the open circuit voltage of the cell under reference case respectively.

The characteristic data for the solarex solex fsm 145w-24 PV panel under the usual test conditions are provided in Table 2 of this article.

Table 2. The solarex solex fsm 145w-24 panel specifications at STC [40].

Electrical specifications	**Values**	***Symbols***
Temperature coefficient of I_{sc} *(A/K)*	0.0065	k_{sc}
Maximum Current *(A)*	4.2	I_{mp}
Parallel cell	1	N_p
Maximum voltage *(V)*	34.4	V_{mp}
Open-circuit Voltage *(V)*	43.5	V_{oc}
Temperature coefficient of V_{oc} *(V/K)*	-0.3609	k_{oc}
Short-circuit current *(A)*	4.7	I_{sc}
Series cells	72	N_{sc}
Maximum power *(W)*	145	P_{mp}

3.3. Effect of Weather Conditions

It is improbable that altering one atmospheric parameter-such as temperature or illumination-will impact the other. These two factors often change simultaneously and in the same direction when they do so at random. The effect of concurrently varying weather conditions on the photovoltaics package is depicted in Figures 3a and 3b.

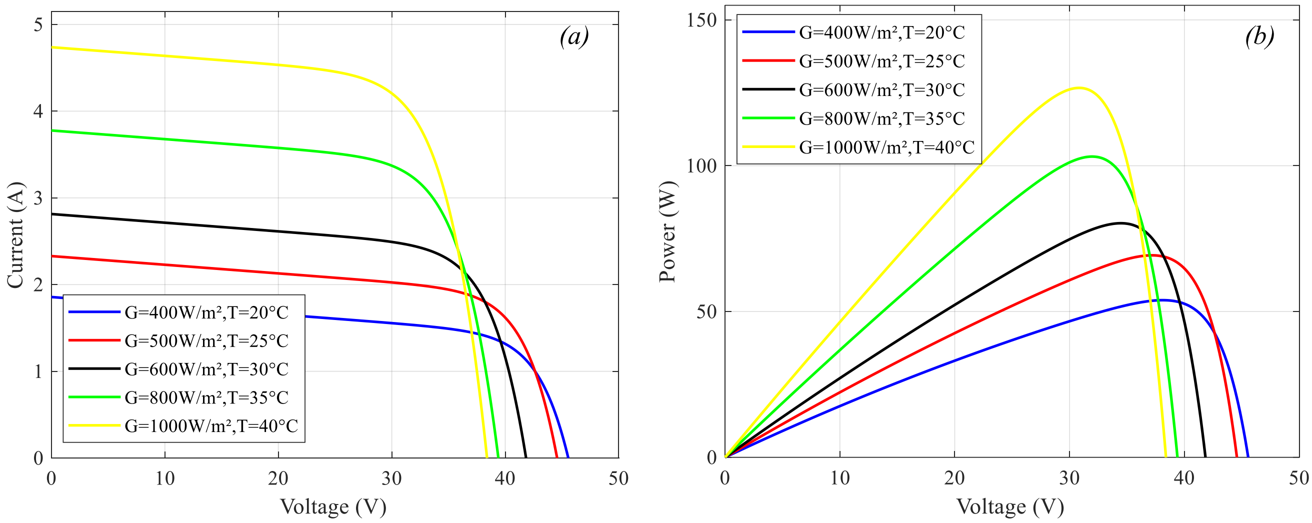

Fig. 3. Effect of temperature and irradiance occurring simultaneously, (a) *I-V* and (b) *P-V* characteristic.

4. Extraction of Maximum Power Point

An MPPT algorithm, in general, is supposed to be able to extract greater energy from the sunlight than a standard power converter. This is why MPPT algorithms may change the panel's working voltage and current in order to optimum power production.

4.1. Problems with the Classic PandO approach

The perturbation and observation (PandO) procedure is based on comparing a PV module's output power to its previous perturbation cycle and on the periodic perturbation of the module's output tension [9–11]. The organization of the P&O MPPT order is shown in Figure 4 [9–11, 14]. To detect the current and tension measurements and calculate the power at each instant, two captures are required. If a tension perturbation requires less power, the direction of the perturbation is not changed. In the opposite scenario, the equation is flipped such that the operational point approaches the maximum power point (MPP).

The classic PandO algorithm is one of the most commonly used algorithms for MPPT in photovoltaic systems. However, it has certain limitations and problems that can affect its efficiency and performance.

- Oscillations around the MPP: the P&O algorithm is sensitive to rapid fluctuations in sunlight conditions. This can lead to oscillations around the MPP, which can result in energy losses and premature wear and tear on system components.

- Slow convergence: the P&O algorithm may have a slow convergence to the MPP, especially when irradiance levels are low. This can lead to a reduction in the system's overall conversion efficiency.

- Problems on cloudy days: when the sky is partly cloudy, the P&O algorithm may interpret fluctuations in sunlight as changes in maximum power, resulting in an erroneous search for the maximum power point.

- Solar cell degradation: repeated cycles of disturbance and observation can cause premature degradation of solar cells, particularly when operating at high power levels.

4.2. Procedure for P&O MPPT Optimization Approach

The proposed MPPT technique is based on the conventional PandO process. The classic P&O algorithm's implementation, shown in Figure 5, has problems that need to be fixed, thus an additional fuzzy logic controller (FLC) block is used to provide a variable step.

The perturbation variable employed in the recommended method is the duty cycle. This ratio is changed by either adding or deleting the step in line with the variation in PV output power. The step, which is not fixed, is calculated by the FLC block [40-43]. The fundamental idea behind the FLC block is to change the step value depending on where the operating point sits. The FLC delivers a high step value when the operating point is far from the PPM. If the operating point is close to the PPM, the pitch value is altered to a low value. This process continues until MPP is reached with a zero step value, ensuring a rapid dynamic response and eliminating fluctuations surrounding MPP when a steady state is obtained.

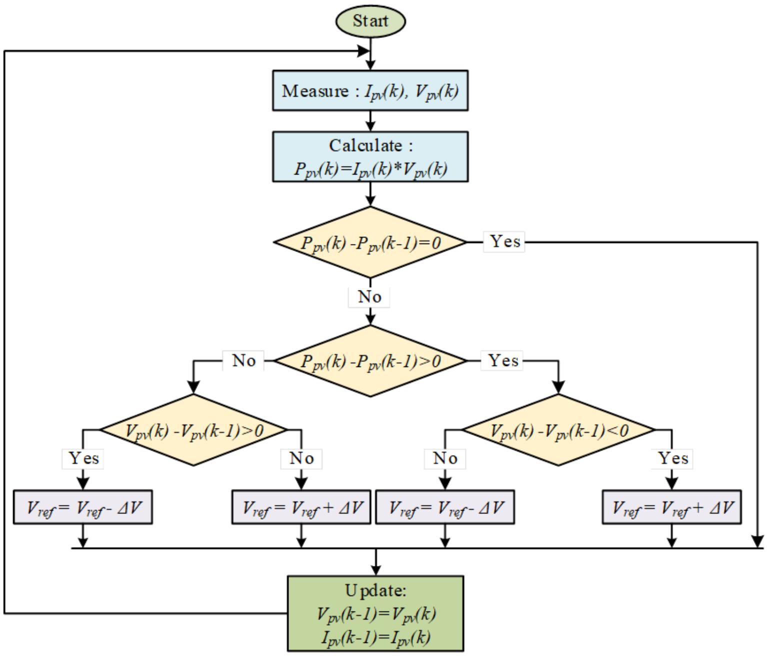

Fig. 4. Conventional P&O algorithm flowchart.

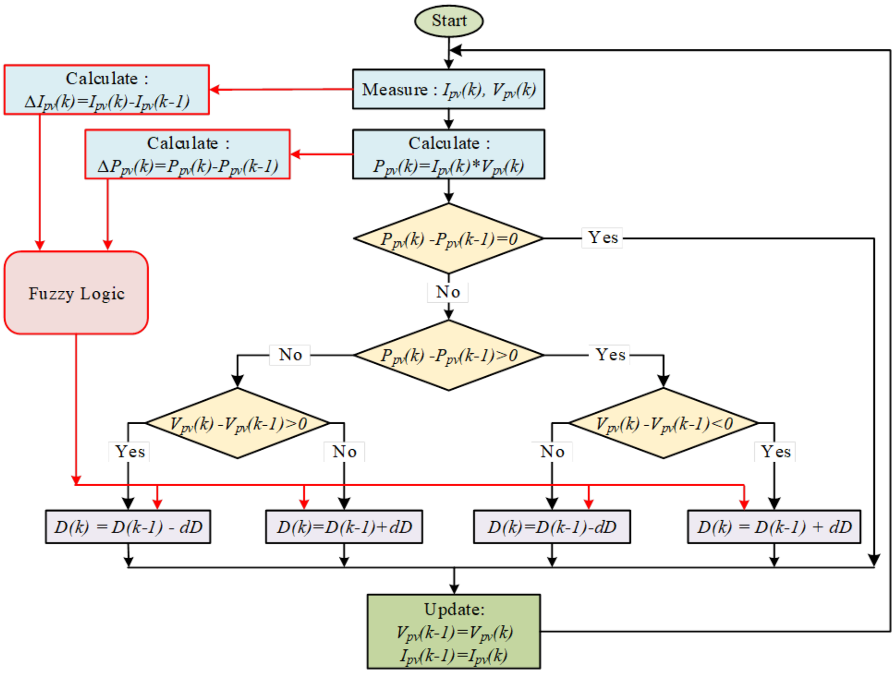

Fig. 5. Flowchart of perturbation and observation strategy improved by FL with a variable step.

5. Experimental Results and Benchmarking

The experimental findings from our investigation are given in this penultimate part, along with a thorough analysis of the findings.

5.1. Experimental Results

An appropriate testbed for experiments has been created. It is used to verify the effectiveness of the perturbation and observation procedure's fuzzy logic with variable step strategy. Figure 6 shows all of the test bench's hardware components [1, 3, 40]. The hardware configuration is made up of several modules that make it possible to measure various specifications, including voltage and current produced by the PV array (thanks to the ST 1000-II sensor and PR20 sensor, respectively). The dSPACE DS1104 board was chosen for its experimental implementation's dependability and resilience. The various blocks used in Matlab/Simulink were then translated using this board. The electricity generated by the solar panel is transferred to the electrical charge using a Semikron power converter. The exact specifications of the IGBT boost converter are shown in Tables 3.We have adjusted the sample frequency for this converter at *10 kHz*. The MPPT approach provided by the real-time interface model on the dSPACE DS1104 board then uses the various signals from the current and voltage created by the solar unit. A pulse width modulation interface card uses this signal to control the inverter.

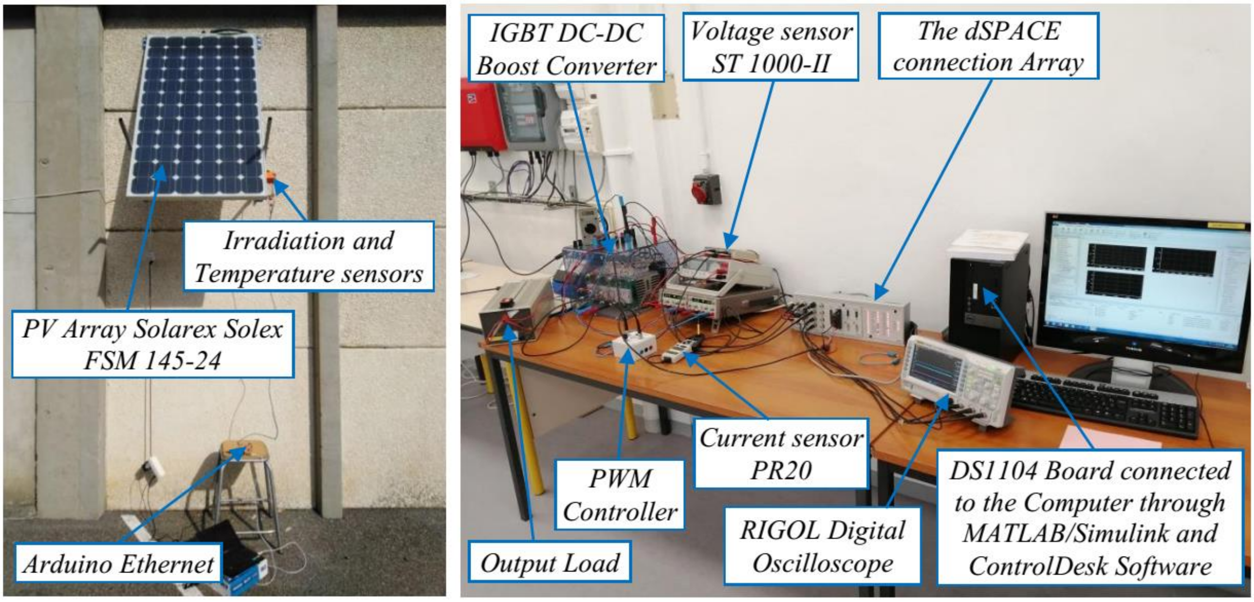

Fig. 6. The hardware configuration used in the experiment.

Table 3. IGBT boost converter specifications [37].

Electrical specifications	Values	*Symbols*
Rated output voltage *(V)*	400	V_{out}
Rated input current *(A)*	30	I_{in}
Rated output current *(A)*	30	I_{out}
Output filter capacitor *(µF)*	47	C_{out}
Boost inductor *(mH)*	1.0	L
Input filter capacitor *(µF)*	90	C_{in}
Switching frequency *(KHz)*	20	f

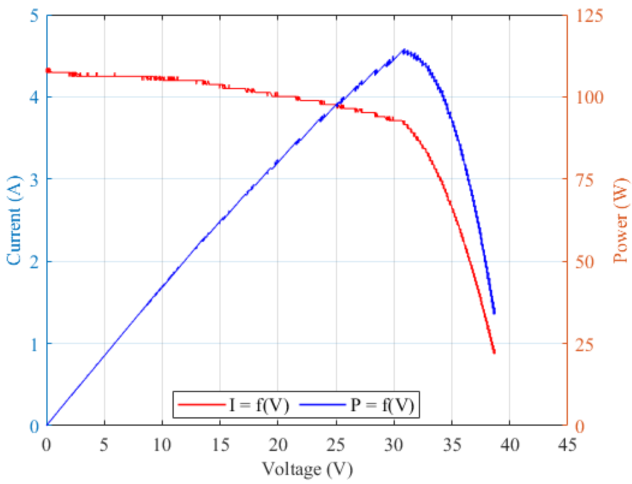

Fig. 7. Experimental graph of I-V and P-V specifications.

Figure 7 displays the actual current-voltage (*I-V*) and power-voltage (*P-V*) measurements of the PV array at 25 °C and 850 W/m² of solar irradiation. The operational point when an electrical charge of ($R = 30\ \Omega$) is connected to a PV devices and the duty cycle is zero (i.e., when no control is applied). The waveforms shown make it clear that the resistive load is running at a substantial distance from the point of peak power. (Vpv = 30.91 V; Ppv = 114.7 W).

We ran experiments utilizing the built test tank to confirm the efficacy of the revised PandO algorithm via fuzzy logic with variable step. The findings are shown in Figure 8 as current, power, and voltage waveforms for both the suggested technique, traditional P&O on panel and converter fronts. It is clear that the modified fuzzy logic-based algorithm performs better than the traditional PandO strategy, particularly in unpredictable operating settings such sudden changes in irradiance. The proposed method really provides a greater level of energy efficiency than the conventional PandO method. Furthermore, the suggested technique reduces oscillations.

5.2. Performance Benchmarking

Table 4 presents the performance benchmarking of the proposed strategy and a comparison with the MPPT strategies that are already accessible in the literature. The characteristics used to compare the suggested method to the already-used technology in the literature include response time, tracking effectiveness, and power harvested at the MPP. Table 4 shows that the recommended approach has a faster reaction time than the traditional perturbation and observation in the literature and is simple to use.

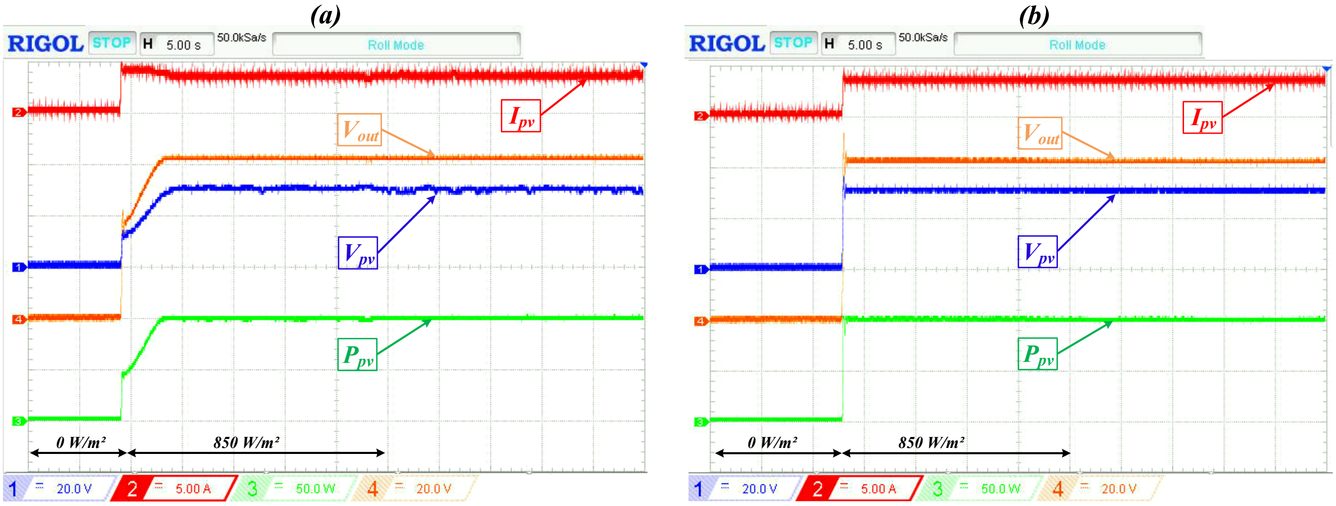

Fig. 8. Results from experiments, (a) classic P&O and (b) improved PandO approach by FLC.

Table 4. Comparison and benchmarking of the recommended technique with earlier literature-based efforts.

Specifications	**Ref [6]**	**Ref [20]**	**Ref [33]**	**Ref [35]**	**Ref [37]**	**Ref [38]**	**Proposed approach**
Efficiency *η (%)*	98	99.37	97.56	98	99	99.39	99.6
Average power P_m *(W)*	4100	60.15	79	200	80	100	100
Reaction time τ_r *(s)*	0.01	0.016	0.03	0.0335	0.1	1.6	0.01
Ripple rate of the power t_o *(W)*	-	-	Less	0.43	0.04	-	0.05
Type of sensors needed	Voltage and current	Current and voltage	Voltage and current	Current and voltage	Voltage and current	Current and voltage	Voltage and current
The difficulty of implementation	Difficult	Easy	Medium	Complex	Easy	Difficult	Easy
Approaches Improvement Strategy	PTD-PandO	M-VSS-PandO	PandO by ACO	PandO by FLC	PandO by FLC	PandO by FLC	PandO by FLC

6. Conclusion

In order to optimize power photovoltaic (PV) utilization, a testing deployment of the enhanced perturbation and observation (PandO) technique by fuzzy logic control (FLC) with variable step has been proposed. The maximum power point tracking (MPPT) PandO approach for PV devices is first reviewed in the literature. The three types of P&O algorithms that have been published in the literature are a modification of the PandO process's fundamental structure, a mixing of the PandO procedure with a traditional approach (such as SMC, FOCV, and FSCC), and an arrangement with another intelligent method (such as, PSO, ANN, and FLC). The suggested procedure's implementation was then offered. The results of the experiments demonstrate that the recommended approach's reaction time is superior to the traditional PandO procedure in terms of benchmarking. Furthermore, it is discovered that the stability and energy fluctuations of the suggested control are virtually completely abolished. With FL's enhanced MPPT P&O control, efficiency, reaction time, and power ripple rate were all at 99.6 %, 0.01 seconds, and 0.05 Watts, respectively. So it is precise and straightforward. Additionally, it offers the MPP quicker convergence as compared to the literature-recommended P&O approach.

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