Experimental Implementation of Improved P&O MPPT Algorithm based on Fuzzy Logic for Solar Photovoltaic Applications

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***Abstract*—In this work, a literature review of the maximum power point tracking (MPPT) perturb and observe (P&O) technique for photovoltaic (PV) systems is first developed. The P&O algorithms available in the literature are distributed through three groups: a modification of the basic structure of P&O method, a combination of P&O techniques with a classical technique (FSCC, FOCV, SMC) and a combination with another smart technique (FLC, ANN, PSO). Subsequently, the experimental implementation of an improved MPPT P&O algorithm based on fuzzy logic (FL) for solar PV applications is proposed. The conventional P&O algorithm is widely used in PV generation systems due to its easy implementation and low cost. Notwithstanding, its main limitation is the trade-off between dynamic response and steady state oscillation. In order to overcome the limitations existing in the implementations of the conventional P&O algorithm, a FL based controller block is used to provide a variable step. The experimental results show that the response time of the proposed technique is better than the conventional P&O technique. In addition, it is found that the power oscillations and stability of the proposed control are almost eliminated. The improved P&O control based on FLC is accurate, simple and allows a faster optimization towards the maximum power point (MPP) relative to the suggested P&O algorithms found in the literature.**

Keywords—Experimental result, MPPT, P&O, Fuzzy Logic, Photovoltaic system.

I. INTRODUCTION

Photovoltaic (PV) energy is becoming more and more a solution among the promising energy options. It has the advantage of being non-polluting and available in large quantities anywhere on the globe. In spite of the technological developments in the manufacture of solar panels dedicated to the transformation of solar radiation into electricity, the latter suffer from rather low energy conversion efficiency. This efficiency may be significantly lower if the PV generator is not operated in accordance with its maximum power point (MPP). Tracking this MPP, which varies location according on the weather, is a critical stage in the design and execution of a PV system. To overcome these problems, it is necessary to introduce an MPPT controller between the load and the PV generator to allow the adaptation of the load to the PV generator [1-3].

Many MPPT techniques for solar PV applications and their implementation are described in the literature [2, 4-5]. The traditional P&O method is widely used and suggested by some authors. These modified algorithms are distributed into three groups and detailed in Table I [6-31]. A suggested P&O MPPT algorithm for PV systems is implemented in [11]. The purpose was to tackle the limitation of instabilities due to the changes in meteorological conditions. Their technique achieved 96% of tracking factor over 90% for the classical approach. The authors in [12] proposed an improved P&O MPPT method to tackle steady state variations and dynamics around the MPP. The average efficiency improvement over the HC approach was in between 1 and 1.1%. In [14], the authors proposed and tested a new P&O technique under varying irradiance levels. Their method offers better performance in terms of tracking accuracy, tracking speed and dynamic efficiency. The authors in [24] proposed and hybrid method, associating P&O and FOCV to achieve direct duty cycle control. After experiment, their method show an improvement over the classical approach around 15% at uniform irradiance and 25% during partial shading. A novel P&O based ASMC under varying load situation is proposed in [23]. They were able to reduce overshoot during spontaneous changes in solar global irradiance and improve the steady state fluctuation.

This work has several objectives. The first is to offer an overview of previous research on P&O MPPT algorithms for solar PV applications and to suggest a brand-new, highly effective and reasonably priced MPPT algorithm. The other goal is to put out a brand-new P&O MPPT control mechanism employing FL by variable step. The layout of the article is as follows: a literature review of previous works of similar modified P&O technique is suggested in Section II. Subsequently, the PV system and an MPPT implementation is highlighted in Section III, emphasizing first on the general design of the proposed PV system, then classic P&O method and finally the approach for the optimization of P&O algorithm. Section IV contains the experimental results and an analysis and discussion of the performance of the proposed technique with some works in the literature, respectively. A conclusion summarizing the key themes is provided at the end of the work.

II. LITERATURE REVIEW OF SIMILAR PREVIOUS WORKS

A literature review of previous work on the improved P&O MPPT algorithm is presented in Table I [6-31]. In this review, we analyzed and classified the works into three groups: a modification of the basic structure of P&O method, a combination of P&O technique with a classical technique (FSCC, FOCV, SMC), and a combination with another smart technique (FLC, ANN, PSO).

TABLE I. OVERVIEW OF AMENDED P&O ALGORITHM FOR MPPT IN PV SYSTEM

Ref	Strategy for improving the MPPT approaches	Converter used and its application	Simulation Tools	Implementation Tools	Comment
Modified the basic structure of the MPPT Perturb and Observe method					
[6]	Power Threshold Decided (PTD) two step sizes P&O	DC–AC Single-phase full-bridge inverter	Matlab/ S-Function	DS 1103 dSPACE	The proposed modified P&O algorithm overcomes these issues by incorporating deadbeat control to achieve faster convergence and steady-state operation at the MPP.
[7]	Two modes step sizes P&O	DC–DC Buck converter for standalone	PSIM	Microcontroller PIC-16F887	Their novel P&O Address the issue of rapid change of the irradiance and load changes due to partial shading. As result they increase the speed and reduce steady state oscillations.
[8]	Drift avoidance (free) P&O	SEPIC DC-DC converter for standalone	Matlab/ Simulink	Arduino Atmega 2560 microcontroller	A P&O method is suggested that incorporates current change in addition to power shift and voltage shift to prevent derating, and the specified approach precisely monitors the maximum power and prevents derating under rapidly changing meteorological conditions.
[9]	Variable step-size P&O	Buck DC–DC converter for standalone	Matlab/ Simulink	Microcontroller (PIC-16F887)	The study aimed to develop a modified P&O MPPT scheme for solar PV systems, which takes into account the response time of the power electronics DC-DC converter, and evaluates its performance parameters under different conditions.
[10]	P&O with dynamic boundary	DC–DC Buck-Boost converter for standalone	Matlab/ Simulink	dSPACE DS1104	This work proposes a suggested P&O MPPT method for PV systems, which dynamically alters the perturbation size and introduces a dynamic boundary condition to reduce steady state oscillation and prevent losing tracking direction.
[11]	Additional loop of calculate load value P&O	DC–DC Boost converter for standalone	Matlab/ Simulink	FRDM-KL25Z development board	Authors implemented a modified P&O algorithm for PV systems in order to tackle the limitation of instabilities due to the changes in meteorological conditions.
[12]	P&O with dynamically after the perturbation step	DC–DC Boost converter for standalone	Matlab/ Simulink	NA	Authors proposed an improved P&O method to tackle steady state variations and dynamics around the MPP. The average efficiency improvement over the HC approach was in between 1 to 1.1%.
[13]	P&O by adding a third parameter	DC–DC Boost converter for standalone	Matlab/ Simulink	NA	This study proposes a revised P&O algorithm to address the two main drawbacks of the basic MPPT P&O method used in PV systems, which increases the speed of optimization and improves the mean efficiency by four percentage points under varying sunlight conditions, without requiring additional hardware components.
[14]	Additional irradiance loop P&O	DC–DC Boost converter for standalone	Matlab/ Simulink	NA (Not Available)	The paper investigates the performance of the classical P&O method in tracking the MPP under sudden and fast-changing solar irradiation and proposes a modified P&O-based-MPP tracking method that performs better in terms of tracking speed, efficiency, and accuracy.
[15]	P&O by the perturbation size (*dV*)	DC–DC Boost converter for standalone	Matlab/ Simulink	NA	This paper proposes a modified P&O method for MPPT in PV system that adaptively determines the perturbation size and direction to increase convergence speed and decrease oscillations, and is capable of extracting maximum power even under sudden or gradual variation in solar irradiation.
[16]	Modified Variable step-size (MVSS) P&O	DC–DC Forward converter for standalone	Matlab/ Simulink	dsPIC30F2010 microcontroller	The paper proposes a MVSS P&O strategy, which overcomes several drawbacks and limitations of previous MPPT methods, and has been demonstrated to offer benefits in terms of low ripple, low overshoot, and low response time, as well as improving transferred available power.
[17]	P&O with Simplified Model-based State Estimation (SMSE)	DC–DC Boost converter for standalone	NA	MCU dsPIC33FJ16GS 502	The paper proposes a new MPPT approach that combines SMSE with adaptive alpha (α-P&O) method, resulting in improved tracking accuracy, reduced tracking time, and tracking energy loss, demonstrated through simulations and experiments, and outperforming conventional and variable step-size P&O algorithms.
[18]	Confined search spaced P&O	DC–DC Boost converter for standalone	Matlab/ Simulink	Arduino Uno	The paper proposes a solar tracker and suggested P&O method to improve the efficiency of standalone solar PV systems, with the algorithm confining the search space of the power curve to 10% area containing the MPP and starting P&O within that space, resulting in a reduction in steady-state oscillations.
[19]	Modified Variable Step-Size (MSS) P&O	DC–DC Boost converter for standalone	Matlab/ Simulink	Arduino Due	The improved algorithms show better performance than conventional algorithms in equilibrium state, pursuit time, and inverter performance, and the MSS P&O algorithm is verified in a material system as efficient with fast pursuit speed and less wobble.
[20]	P&O by model reference adaptive control (MRAC)	DC–DC Boost converter and Three-phase grid-integration mode grid-connected	Matlab/ Simulink	OPAL-RT simulator (OP-4510)	This study proposes a robust model reference adaptive control (MRAC) for MPPT in PV systems integrated into various modes of transportation and compares it with existing techniques, achieving efficient and faster MPP tracking under fluctuating radiation and temperature conditions.
[21]	Improved drift-free P&O	Quadratic Boost converter for stand-alone PEMFC	Matlab/ Simulink	NA	The study proposes a drift-free MPPT algorithm to improve energy harvesting capacity for fuel cells in dynamic conditions, using current change information in addition to power and voltage changes.
[22]	P&O by model reference adaptive control (MRAC)	DC–DC Boost converter for standalone	Matlab/ Simulink	NA	The suggested controller has simple layout, higher dynamic responsiveness, quick convergence time, strong efficiency and insignificant oscillations near the MPP.
Combined the classical MPPT P&O method with one or more classical MPPT methods					
[23]	P&O with Fractional Short Circuit Current (FSCC)	DC–DC Boost converter for standalone	Matlab/ Simulink	dSPACE DS1104 card	The authors provide experimental results to validate the effectiveness of the proposed algorithm, showing its ability to track the MPP under different operating conditions.

[24]	P&O with Fractional Open circuit voltage (FOCV)	DC–DC Boost converter for standalone	NA	The ATmega328 microcontroller	Authors proposed and hybrid method, associating P&O and FOCV to achieve direct duty cycle control. After experiment, their method show an improvement over the classical approach around 15% at uniform irradiance and 25% during partial shading.
[25]	P&O with Adaptive Sliding Mode Control (ASMC)	DC–DC Boost converter for standalone	Matlab/ Simulink	NA	The control method is based on P&O and uses SMC to estimate the system states. The proposed method is designed to ensure stable and efficient operation of the PV system under different load conditions.
Associated the classical MPPT P&O method with one or more so-called intelligent MPPT methods					
[26]	P&O with Colony Optimization (ACO)	DC–DC Boost converter for standalone	NA	PIC16F876A Digital Controller	Their new method uses a hybrid approach, which combine ant colony and P&O. It improves statics and dynamics GMPP convergence characteristics.
[27]	P&O with Grey Wolf Optimization (GWO)	DC–DC Boost converter for standalone	Matlab/ Simulink	dSPACE 1104	The initial stage of the tracking is done through the GWO. The P&O algorithm is computed at the final stage. The proposed method possess better tracking performance.
[28]	P&O with Fuzzy Logic (FL)	DC–DC Boost converter for standalone	Matlab/ Simulink	dSPACE DS 1104 board	Authors implemented a modified P&O in a FL controller with minimum rule to reduce computational needs. Their approach present high dynamic performance under various situations.
[29]	P&O with Artifcial Neural Network (ANN)	DC–DC Boost converter for standalone	Matlab/ Simulink	NA (Not Available)	Authors combine Artificial neural network with P&O. ANN predict the MPP region and P&O search the MPP in that region. The technique achieves greater PV arrays power output level.
[30]	P&O with Fuzzy Logic (FL)	DC–DC Boost converter for standalone	Matlab/ Simulink	dSPACE DS4002 board	The authors explain the advantages of using FL in MPPT, which includes the ability to handle imprecise information and non-linearity.
[31]	P&O with butterfly particle swarm optimization (BPSO)	DC–DC Boost converter for standalone	Matlab/ Simulink	Arduino Uno Rev3 board	The proposed method combines the BPSO and P&O algorithms to improve the accuracy and convergence speed of MPPT. The BPSO algorithm is used to find the initial value of the duty cycle, while P&O algorithm is used to track the MPP.
this study	P&O by Fuzzy Logic (FL) with a variable step	DC–DC Boost converter for standalone	Matlab/ Simulink	dSPACE DS 1104 board	Authors implemented a modified P&O by FL with a variable step controller with minimum rule to reduce computational needs. Their approach present high dynamic performance under various situations.

III. PV SYSTEM AND MPPT IMPLEMETATION

In this section, we will explain the suitable implementation of the proposed model and the optimization approach of the traditional MPPT P&O method based on FL.

A. Overall design of the proposed photovoltaic system

Fig. 1 displays a synoptic diagram outlining the experimental setup for a PV system. The system includes a solar PV array of type Solarex Solex FSM 145-24, a semikron power converter, a DS1104 test equipment responsible for MPPT, a laptop and a load, and a load. Since the efficiency of the PV field is temperature-dependent and solar irradiations are constantly shifting, the MPPT method must account for these variables, which is done through the use of the boost power converter. The power shifts and their derivatives are utilized as input variables for the MPPT technique through the DS1104 test board. The PC logged to the dSPACE, equipped with Matlab/Simulink and Controldesk program, is responsible for implementing the MPPT approaches and generating the PWM signal required to operate the boost converter.

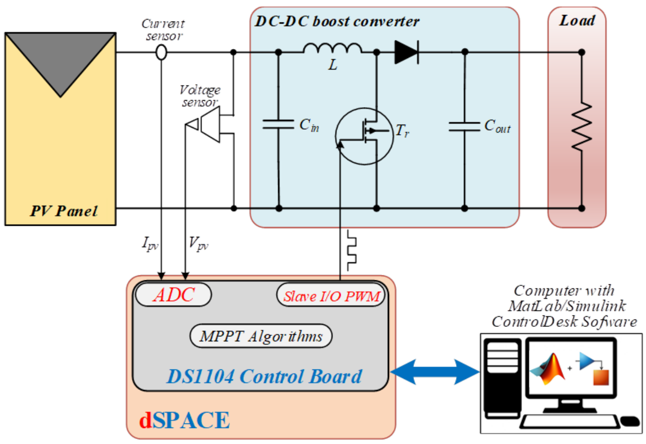

Fig. 1. Diagram of the experimental setup of the proposed PV system.

In reality, the change of one atmospheric parameter (illumination or temperature) by fixing the other is unlikely. Generally, the change of these two parameters that occurs randomly is in most cases simultaneous and in the same direction. Figure 2a-b shows the impact of simultaneous variation of weather conditions on the PV module.

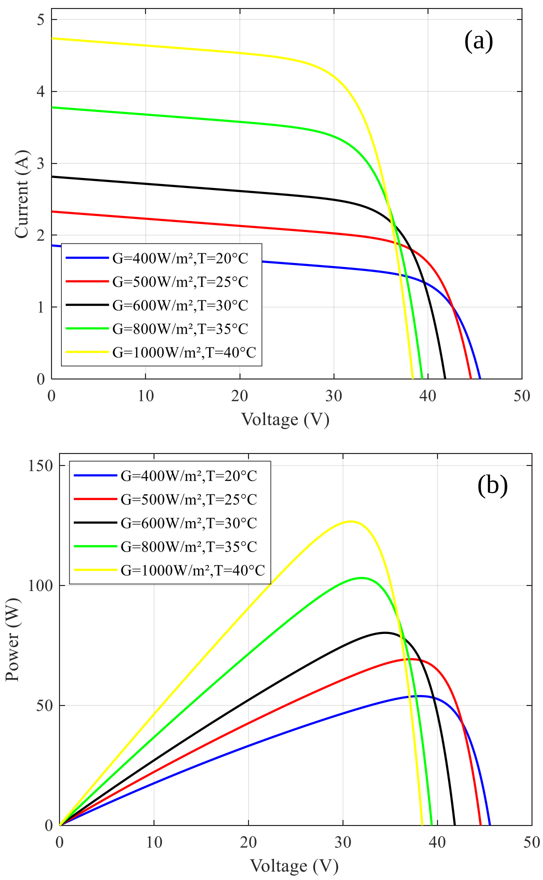

Fig. 2. Simultaneous effect of irradiance and temperature, (a) on the I-V and (b) on the P-V characteristic.

B. Conventional P&O Algorithm

The Perturb and Observe (P&O) approach is based on comparing the output power of a PV module with its prior disturbance cycle and periodically perturbing the voltage at the module's output [9-11]. The P&O MPPT command's flowchart is shown in Fig. 3 [9-11, 13]. Two sensors are required to detect the current and voltage values in order to calculate the power at each instant. If the power diminishes for a voltage disturbance, the disturbance preserves its direction. If not, the equation is turned around such that the operational point moves closer to the MPP.

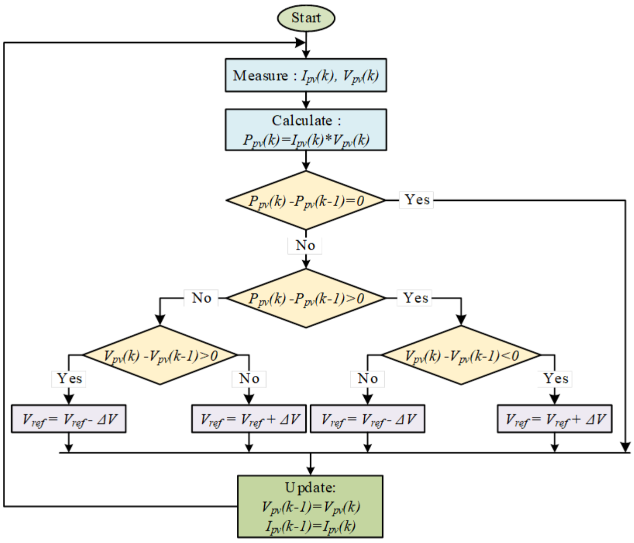

Fig. 3. Flowchart of the conventional P&O algorithm.

C. Approach for the optimization of the MPPT P&O algorithm

The traditional P&O algorithm serves as the foundation for the suggested MPPT algorithm. To get around the issues with the traditional P&O algorithm's implementation, as illustrated in Fig. 4, an extra fuzzy logic controller (FLC) block is employed to give a variable step.

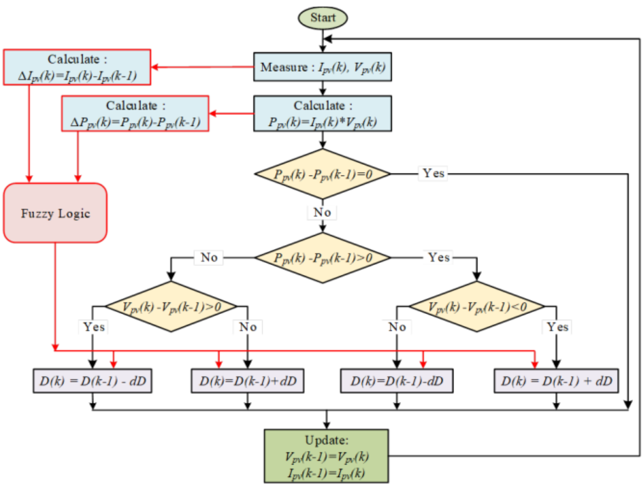

Fig. 4. Flowchart of P&O algorithm improved by fuzzy logic with a variable step.

The duty cycle is the perturbation variable used in the suggested approach. In accordance with the fluctuation in PV output power, this ratio is altered by either adding or removing the step. The FLC block [32] calculates the step, which is not fixed. The FLC block's guiding concept is to modify the step value in accordance with where the operational point is located. When the operating point is distant from the PPM, the FLC outputs a high step value. The pitch value is changed to a low value if the operating point is near to the PPM. With a zero step value, this procedure continues until MPP is attained, ensuring a quick dynamic reaction and removing oscillations around MPP when a steady state is established.

IV. Experimental Results and Discussion

In this section, we will present the experimental results of our study and provide a detailed discussion on these findings.

A. Experimental results

A suitable experimental testbed has been built. It is used to validate the performance of the strategy of the P&O MPPT method improved by fuzzy logic with a variable step. The different hardware elements of this test bench are depicted in Fig. 5 [1, 3, 32]. The testbed is composed of different modules that allow to measure different parameters such as voltage (thanks to the ST 1000-II sensor) and current (thanks to the PR20 sensor) produced by the PV system (via the Solarex Solex FSM 145-24 solar module). The dSPACE DS1104 board was chosen for its robustness and reliability of experimental implementation. This board was then used to translate the different blocks implemented in Matlab/Simulink. A Semikron power converter is used to transfer the power produced by the solar panel to the load. To control this converter, we have set the sampling frequency to 10 *kHz*. Then, the different signals from the voltage and current generated by the solar module are used by the MPPT algorithm offered via the Real-Time Interface (RTI) model on the dSPACE DS1104 board. This produces a signal that drives the inverter via a pulse width modulation interface board.

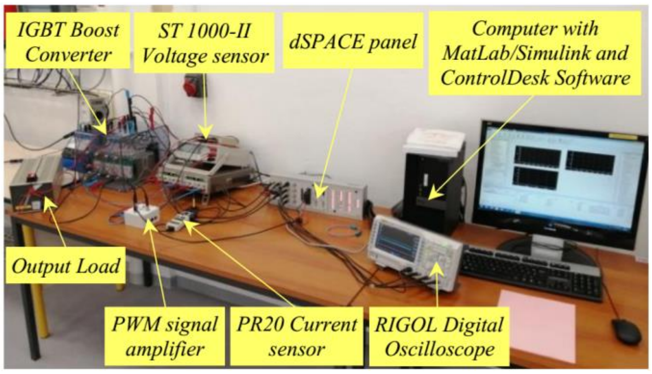

Fig. 5. The experimental hardware setup.

The real current-voltage (*I-V*) and power-voltage (*P-V*) characteristics of the Solarex Solex FSM 145W-24 PV array are shown in Fig. 6, at a temperature of 25 °C and a solar irradiance of 850 W/m². The operating point with a resistive load of (R = 30 *ohm*) that is coupled to the PV module when the duty cycle is zero (i.e. without any control). It is readily apparent from the waveforms displayed that the resistive load is operating significantly distant from the position of peak power. (P_{pv} = 114.7 W, V_{pv} = 30.91 V).

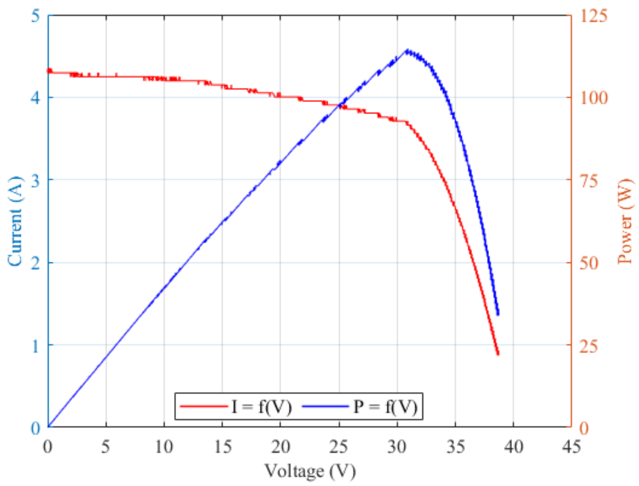

Fig. 6. Experimental curve of the current voltage and power voltage characteristics.

To verify the effectiveness of the improved P&O MPPT algorithm by fuzzy logic with variable step, we performed tests using the test tank that was developed. The results in Fig. 7 show the waveforms of current, power and voltages on the panel and converter side of the proposed algorithm and conventional P&O. It can be noticed that the improved fuzzy logic based algorithm has a better performance than the conventional P&O algorithm, especially under unstable operating conditions such as abrupt irradiance changes. Indeed, the proposed algorithm achieves higher energy efficiency than the traditional P&O algorithm. Moreover, the oscillations are attenuated with the proposed algorithm.

B. Benchmarking and performance comparison

The performance evaluation of the suggested algorithm and the comparative analysis with the available MPPT techniques in the literature are summarized in Table II. The parameters such as: tracking efficiency, response time, and power extracted at the maximum power point allow assessing the proposed method with the existing technique in the literature. From Table II, we can see that the suggested technique is easy to implement and has a higher response time than the classical P&O in the literature.

V. Conclusion

In this paper, an experimental implementation of the improved perturb and observe (P&O) algorithm by fuzzy logic (FL) with variable step for solar photovoltaic (PV) applications has been discussed. First, a literature review of the maximum power point tracking (MPPT) P&O technique for PV systems is developed. The P&O algorithms available in the literature distributed through three groups: a modification of the basic structure of the P&O method, a combination of the P&O technique with a classical technique (FSCC, FOCV, SMC) and a combination with another smart technique (FLC, ANN, PSO). Subsequently, the implementation of the proposed technique was developed. The experimental results show that the response time of the proposed technique is better compared to the conventional P&O technique. Moreover, it is found that the power oscillations and stability of the proposed control are almost eliminated. The improved MPPT P&O control by FL has achieved an efficiency, a response time and a ripple rate of the power of 99.6%, 0.01 s and 0.05 W respectively. It is then accurate, simple and provides faster convergence to the maximum power point compared to the modified P&O algorithms available in the literature.

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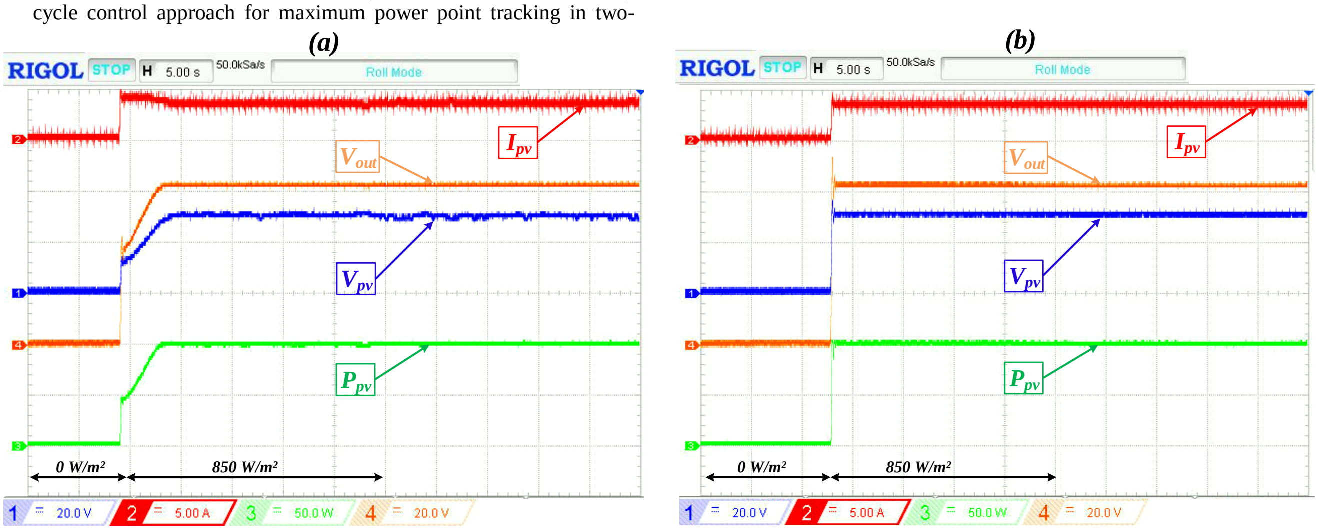

Fig. 7. Experimental results of (a) conventional P&O and (b) implroved P&O MPPT algorithm by FLC.

TABLE II. BENCHMARKING AND COMPARISON OF THE SUGGESTED APPROACH WITH PREVIOUS WORKS IN THE LITERATURE

Designations	**Ref [6]**	**Ref [19]**	**Ref [26]**	**Ref [28]**	**Ref [30]**	**Ref [31]**	**Proposed method**
Average power P_m *(W)*	4100	60.15	79	200	80	100	100
Efficiency η *(%)*	98	99.37	97.56	98	99	99.39	99.6
Response time τ_r *(s)*	0.01	0.016	0.03	0.0335	0.1	1.6	0.01
Type of sensors needed	V and I	I and V	V and I	I and V	V and I	I and V	V and I
Ripple rate of the power t_o *(W)*	-	-	Less	0.43	0.04	-	0.05
Strategy for improving approaches	PTD-P&O	M-VSS-P&O	P&O with ACO	P&O with FLC	P&O with FLC	P&O with FLC	P&O based FLC
Complexity of deployment	Complex	Simple	Medium	Higher	Simple	Complex	Simple