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Simulation and Experimental Assessment of Various MPPT Methods for Photovoltaic Systems

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Abstract

Maximum Power Point Tracking (MPPT) is a power electronic system used to control the electrical circuit that interfaces with the photovoltaic array and adjusts the electrical operating point of the module to operate at its MPP. Several methods have been developed over the years to implement MPPT effectively. This paper covers the simulation and experimental implementation of several MPPT methods. Among these methods are conventional, hybrid, and soft competing methods. The simulations were carried out using MATLAB/SIMULINK. The Arduino Mega 2560 controller implemented the hardware configuration and real-time data acquisition. All experimental work is done at the Renewable Energies Laboratory of the University of Jijel. A thorough explanation of the platforms for implementing software and hardware is given. Test the flexibility and comparison of the MPPT technique has been performed. The results of MPPT methods obtained from simulation and experimental setups were presented and discussed.

Keywords: MPPT techniques; Implementation; Photovoltaic system; MATLAB/Simulink.

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1. Introduction

The International Energy Agency (IEA) has released its annual report, projecting that the world's renewable electricity capacity will increase by over 60% from 2020 levels to more than 4,800 GW by 2026 [1]. This represents the equivalent of the current total global energy capacity from nuclear power and fossil fuels combined. The report forecasts that renewable energy will account for approximately 95% of the global energy capacity growth through 2026, with solar photovoltaics alone contributing to more than half of this increase [2-3].

In order to increase PV system efficiency using MPP tracing, MPPT controllers have been used. 1968 saw the introduction of the first PV system with MPPT for a space system [4-5]. Following that, there was a sharp increase in the dependability, precision, speed, efficiency, and simplicity of MPPT controllers. The best MPPT algorithm often follows the quick changes in output power and operates at a high speed with minimal oscillations around the maximum power point (MPP). Today, there are a lot of applicable MPPT control methods accessible [6]. These controllers were used to monitor a photovoltaic system with several maximum power points or the MPP under uniform illumination for a single MPP [7].

A power electronic system is called Maximum Power Point Tracking (MPPT)that is used for controlling the electrical circuit that interfaces with the photovoltaic array to adjust the electrical operating point of the module such that it operates at its MPP [8]. This is done because the MPP of a solar power device depends on the temperature and the irradiation level. Because of this, if the electrical resistance of the load is fixed, the operating voltage of the PV module will have to be changed to obtain the maximum power [9]. In general, the system controller makes a decision based on the estimated MPP to adjust the required voltage. This is done by continuously sweeping the operating voltage of the PV array and measuring the power output. Once the power output has been calculated, it is compared to the power output at the previous voltage increment. The controller then increases the voltage and continues the process [10-11-12].

In the literature, different categories of MPPT have been presented. These methods can be broadly categorized into two groups: advanced methods and traditional methods [13]. Traditional MPPT techniques are commonly used because they were introduced a long time ago. They are valued for their simplicity and ease of implementation. However, these techniques are limited to monitoring the power point of solar systems under certain conditions [14]. The well-known traditional methods are the perturb and observe (P&O), hill climbing (HC), fuzzy logic control (FLC), artificial neural network (ANN) and, incremental inductance (In Cond) etc. [15-16]. On the other hand, advanced MPPT

techniques, such as artificial intelligence (AI) or bioinspired (BI) methods, have been developed [17-18]. These advanced techniques outperform traditional approaches in tracking despite being relatively complex. As a result, they are capable of extracting the global power point maximum (GMPP) in situations of partial shading. The most used GMPPT methods in the science are partial swarm optimization (PSO), gray wolf optimization (GWO) and Ant colony optimization (ACO) [19]. The latest developed modern bioinspired (BI) methods for tracking the GMPPT are: Horse Herd Optimization (HAO), Flying Squirrel Search Optimization (FSSO) and Salp Swarm Algorithm (SSA) [20]. The goals of this paper are to simulate and test the performance of various MPPT methods in two types of weather: uniform irradiation conditions (UICs) and non-uniform irradiation conditions (N-UICs). The simulated and verified experimental MPPT methods are P&O, modified version of P&O, In Cond, modified version of InCond, HC, FLC, adaptive P&O_FL and, PSO method [21-22].

Enhancing the efficiency of photovoltaic systems requires reliable extraction of maximum power under constantly changing conditions such as irradiance, temperature, and partial shading. To address this challenge, numerous MPPT techniques—ranging from classical P&O and INC methods to optimization-based and intelligent algorithms—have been proposed. However, their reported performance varies significantly depending on the models, panel characteristics, environmental assumptions, and evaluation metrics used in different studies. This variability makes it difficult to determine which approach is truly the most suitable in real-world applications. Moreover, simulation outcomes often fail to match experimental results, adding further uncertainty. Consequently, a major issue arises: identifying the MPPT method that best balances rapid tracking, accuracy, stability, and implementation simplicity[23]. This highlights the need for rigorous comparative assessments, combining both simulation and experimental validation, to better understand the actual behavior of different MPPT strategies under varying operational conditions [24].

The main objective of this work is to provide a comprehensive experimental benchmarking of eight widely used MPPT algorithms implemented on a unified low-cost hardware platform. Unlike many previous comparative studies that are limited to simulation-based evaluations or a reduced number of algorithms, this study combines MATLAB/Simulink simulations with real-time implementation using an Arduino Mega 2560 controller. All algorithms are evaluated under identical operating conditions, including uniform and dynamically varying irradiation levels, ensuring a fair and consistent performance assessment. This approach offers practical insights into implementation complexity, dynamic response, and steady-state behavior, thereby bridging the gap between theoretical analysis and real-world applications.

The structure of the paper is as follows: Section II presents a description of the test bench, and provide a thorough explanation of the hardware and software. Section III presents an Experimental setup. Section VI present results and discussions, Finally, A conclusion is given in Section V.

2. Description of the test bench

In this section, we presented the test bench carried out at the RELab. As shown in Figure 1, The test bench consists of the following elements: a GPV, a chopper type DC/DC converter, a resistive load, current and voltage sensors, a digital oscilloscope, DC power supply, Arduino Mega 2560 bord and a computer.

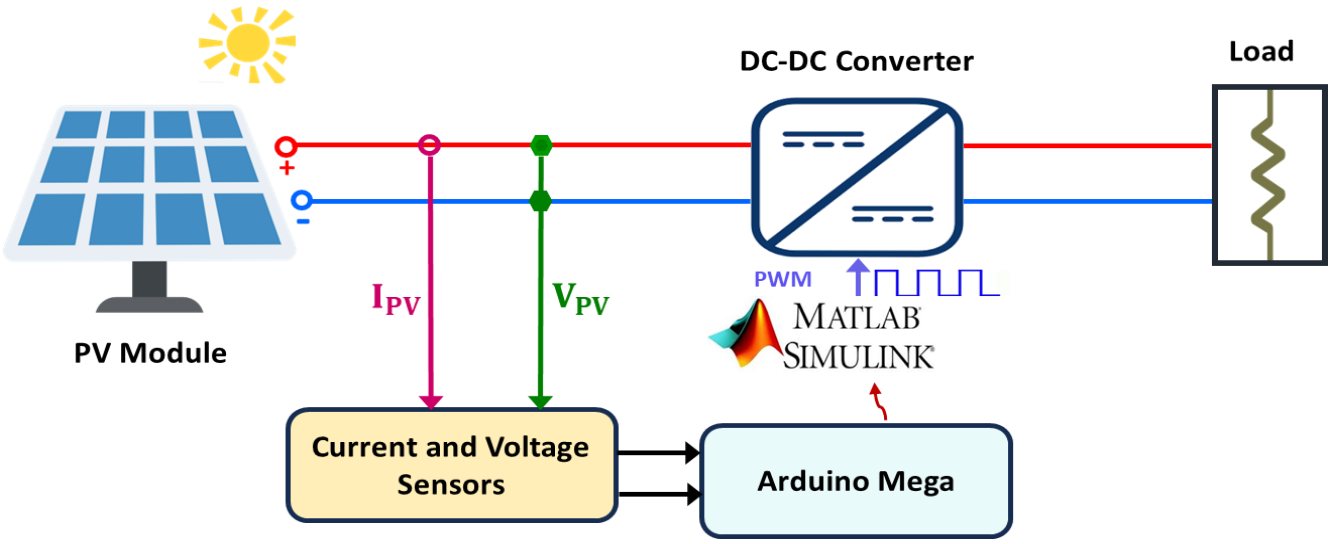


Figure 1. Photovoltaic system architect.

2.1.Hardware Design

This subsection describes the hardware architecture of the test bench of photovoltaic system and explains the main parts of the system. The PV module type that is being used is the MSX- BP Solar 120 watts, which is produced using multi-crystalline technology. Table 1 displays its electrical parameters under standard test conditions (STC: 1000 W/m2 and 25 °C).

A DC-DC chopper converter is a device that provides highly efficient, dependable, and flexible electrical power regulation in DC circuits. Figure 2 shows the electrical circuit of the chopper converter. Its primary components are two switches (MOSFET, Diode), two capacitors (Cint, Cout), and an inductance (L). The values of the utilized components are compiled in Table 2.

Table 1. Specifications of the MSX-120 solar module

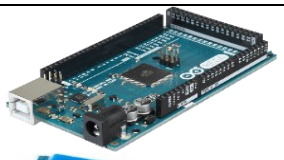
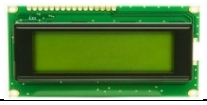
Description	**Value**
Open circuit voltage (Voc)	42.1 V
Short circuit current (Isc)	3.87 A
Rated voltage (Vmpp)	33.70 V
Rated current (Impp)	3.56 A
Rated power (Pmax)	120 W

Table 2. DC-DC Chopper specifications

Description	Value
Input capacitor (Cint)	50 µF
Output capacitor (Cout)	220 µF
Bobin (L)	1 mH
Load (lamp)	5 W - 12 V
Frequency	25 KHz

A data acquisition system is created to gather, process, save, and transmit information from the data acquisition board Arduino Mega and voltage and current sensors to control the designed DC-DC chopper. Below are the main components of the data acquisition system designed for PV systems. In Table 3, it is important to note that the parts used to create the data acquisition system are easily obtainable in the market and are reasonably priced. The total cost of the designed data acquisition system is estimated to be 21.41 $.

Table 3. The reset component of prototype.

Components	Role /cost	Figure
Arduino Mega 2560 Bord	Acquisition Measurement data the and control DC-DC chopper 10.67$	
Sensor voltage	Measurement of the output voltage of the PV Module (Vpv) 2.3$	
Sensor current AllegroACS712	Measurement of the output current of the PV Module (Ipv) 2.1$	
LCD screen 16x4	Show the values of measurement parameters 6.34 $	

2.2. Software Design

In this work, we are not intended to give theoretical backgrounds about the used algorithms: Perturb and Observe (P&O), modified version of (P&O), Incremental Conductance (In Cond), modified version of (In Cond), Hill Climbing (HC), modified version of In Cond, FLC, adaptive P&O_FL and, PSO method, as these algorithms are already developed and simulated. So, in this study, we will focus more on the simulation and experimental implementation in an Arduino board microcontroller of these methods. The MPPT method using the Simulink library is used to determine the duty cycle of the

DC/DC step-up chopper in use, and the Arduino Mega 2560 board is directly used to provide the PWM signal control. As previously indicated, for acquisition and control. The MOSFET transistor of the chopper converter is controlled by the first board, which also implements MPPT algorithms. One DC-DC converter with a switching frequency of 25 kHz and a PWM generator make up the power stage interface between the PV module and the load. The MPPT controller calculates the necessary duty cycle and transmits it to the PWM generator based on the measured Ipv and Vpv. The latter changes the duty cycle of the MPPT into a PWM signal that activates and deactivates the power switch of the DC-DC chopper .

3. Experimental Setup

The facility test has been carried out at the Renewable Energies Laboratory of the University of Jijel. Figure 5 shows the hardware implementation platform that was utilized for the MPPT technique's experimental evaluation and implementation. The test bench includes a DC-DC chopper converter, digital oscilloscope, resistive load, a computer for display results, and a data acquisition board that consists of an Arduino Mega Board, current and voltage sensors, and an LCD screen. Figures 3-4 show the designed DC-DC chopper converter and the data acquisition board, respectively.

During experimental testing, irradiance levels were monitored using a calibrated reference solar cell. The reference cell is installed in the same plane and orientation as the photovoltaic panels to ensure accurate irradiance measurement. Solar irradiance is determined by measuring the voltage across two resistors integrated within the reference cell. The system is calibrated using a pyranometer and a luxmeter, with a calibration coefficient of K=1000.The voltage and current sensors were calibrated using a precision digital multimeter prior to data acquisition to correct offset and gain errors [5].

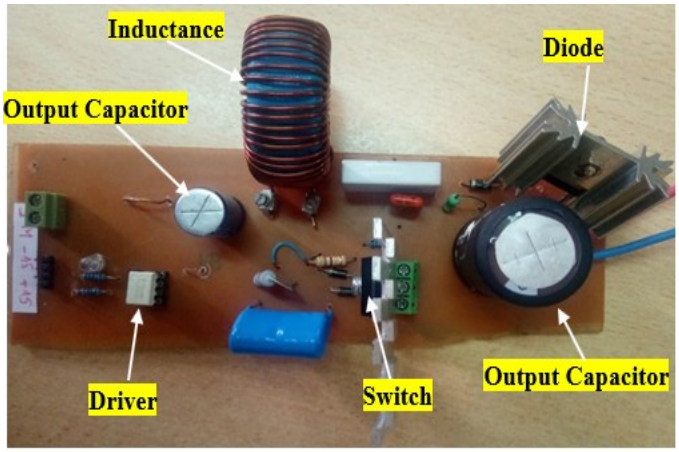


Figure 3. DC-DC chopper converter.

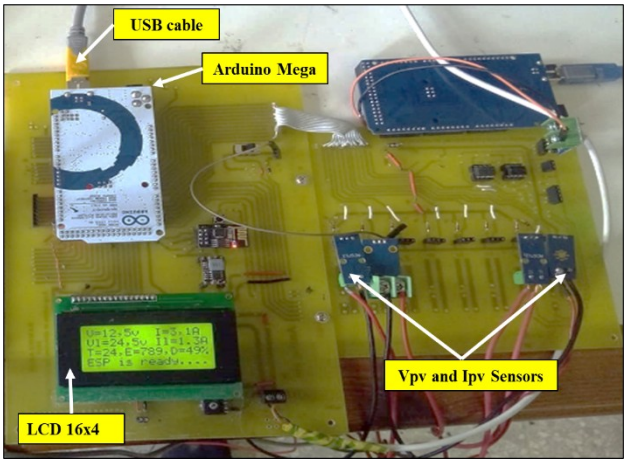


Figure 4. Data acquisition board.



Figure 5. Data acquisition board.

4. RESULTS AND DISCUSSION

4.1. SIMULATION RESULTS

In order to evaluate the effectiveness of the MPPT methods, we conducted various simulations using the MATLAB/Simulink software under different conditions. These conditions included uniform irradiation and rapidly changing atmospheric conditions. Figure 6 illustrates the implementation of the entire standalone photovoltaic system using MATLAB/Simulink. The key components involved are the PV generator, two blocks for current and voltage sensors to measure Ipv and Vpv, a resistive load, a DC/DC chopper converter, and a PWM generator.

- **Simulation under uniform irradiation conditions**

Temperature T = 25 °C is maintained constant during this test and each method is tested with a uniform irradiation level. The results obtained using the test under UICs are presented in Figure 7(a-b-c-d). When the MPPT algorithms search on the MPP, the optimum voltage and current cause oscillations in PV voltage and current. These current and voltage oscillations result in power oscillations. Figure 7 (a-b-c-d), shows that the convergence time of all the methods will not drop back to 0.03 seconds except the P&O method, which takes almost 0.05 seconds. The output power is stable as shown in Figure 7(c-d), except with the two methods P&O and InCond (see figure 7-a-b), which contain small oscillations around the MPP.

- **Simulation under variations of irradiation levels**

This test maintains a constant temperature of T = 25°C while introducing various irradiation step adjustments. The initial irradiation is between G = 400W/m and 800 W/m, then increased and

decreased. The results obtained are presented in figure 8. Figure (8-c) shows that there are oscillations around MPP and a slow response when there is a change of irradiation levels for the HC method, especially in the low irradiation levels of 200 W/m2. On the other hand, the LF method presents a faster response during irradiation changes, and oscillations are almost neglected. Figure (8-e) shows that the PSO and P&O_FL methods show oscillations at the beginning of the MPP search but have a faster response during irradiation change.

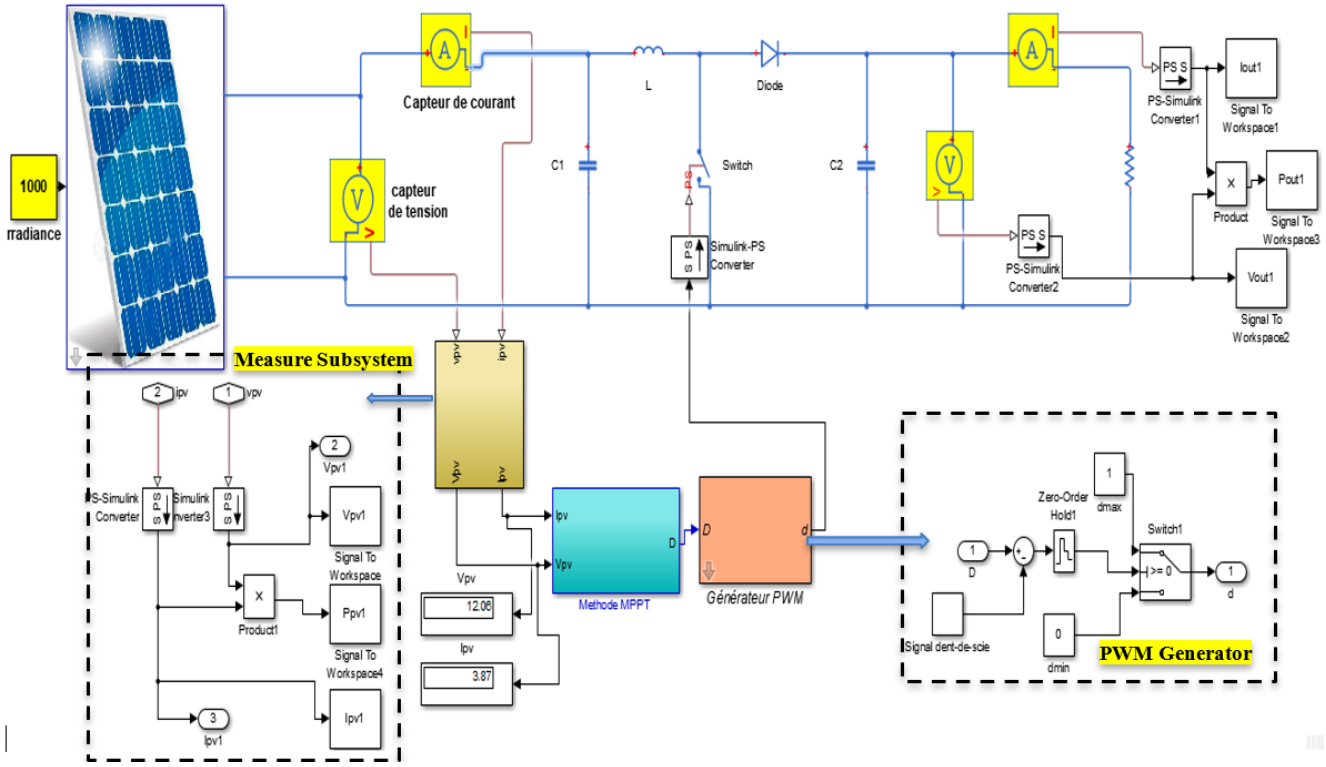
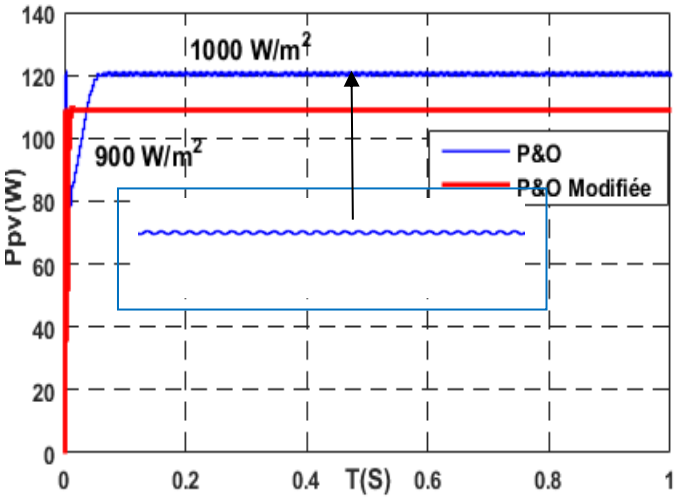
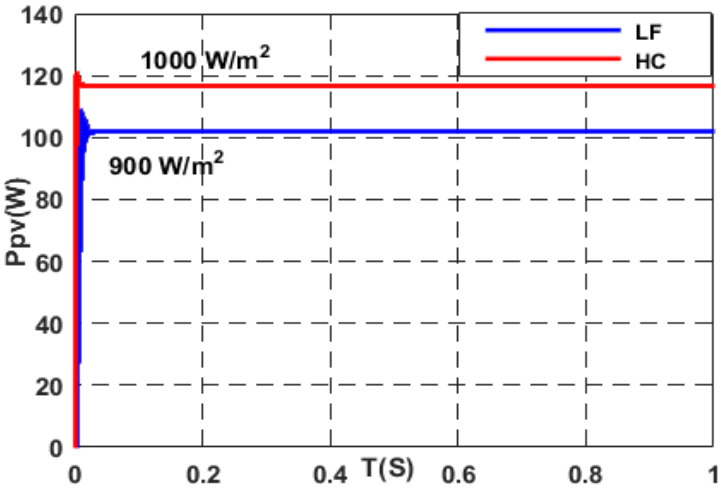


Figure 6. Model of a stand-alone PV system using MATLAB/Simulink.



(a)



(b)

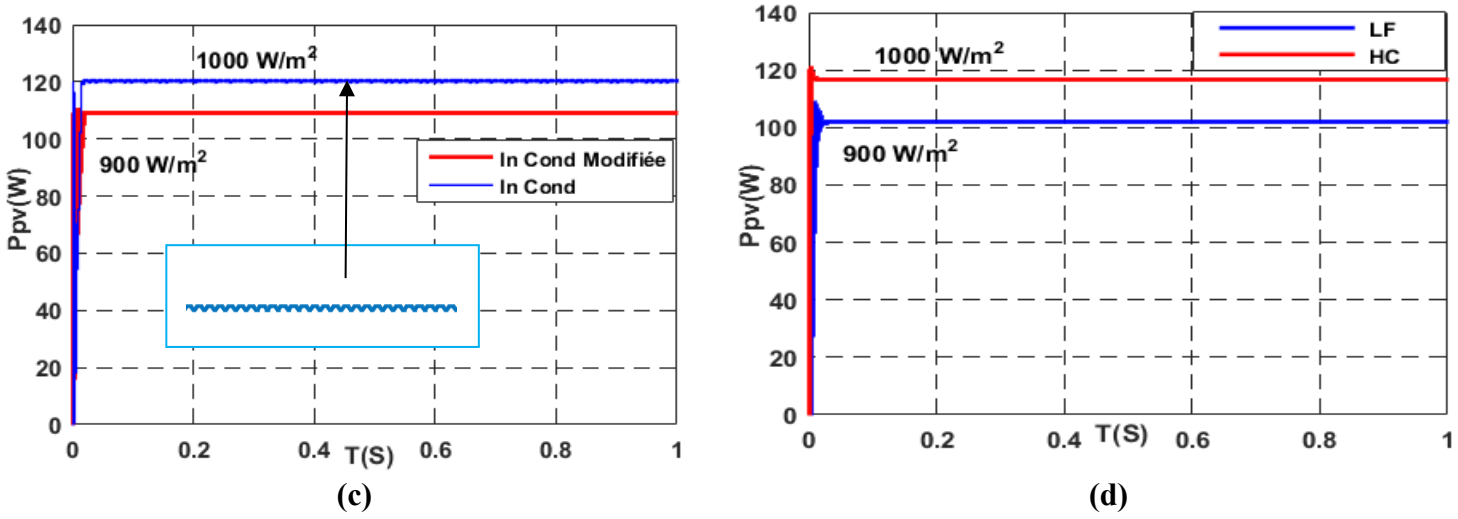


Figure 7. PV power of different MPPTs methods: a) P&O and InCond methods; b) P&O and modified In Cond; c) HC and LF; d) Adaptive P&O_LF and PSO.

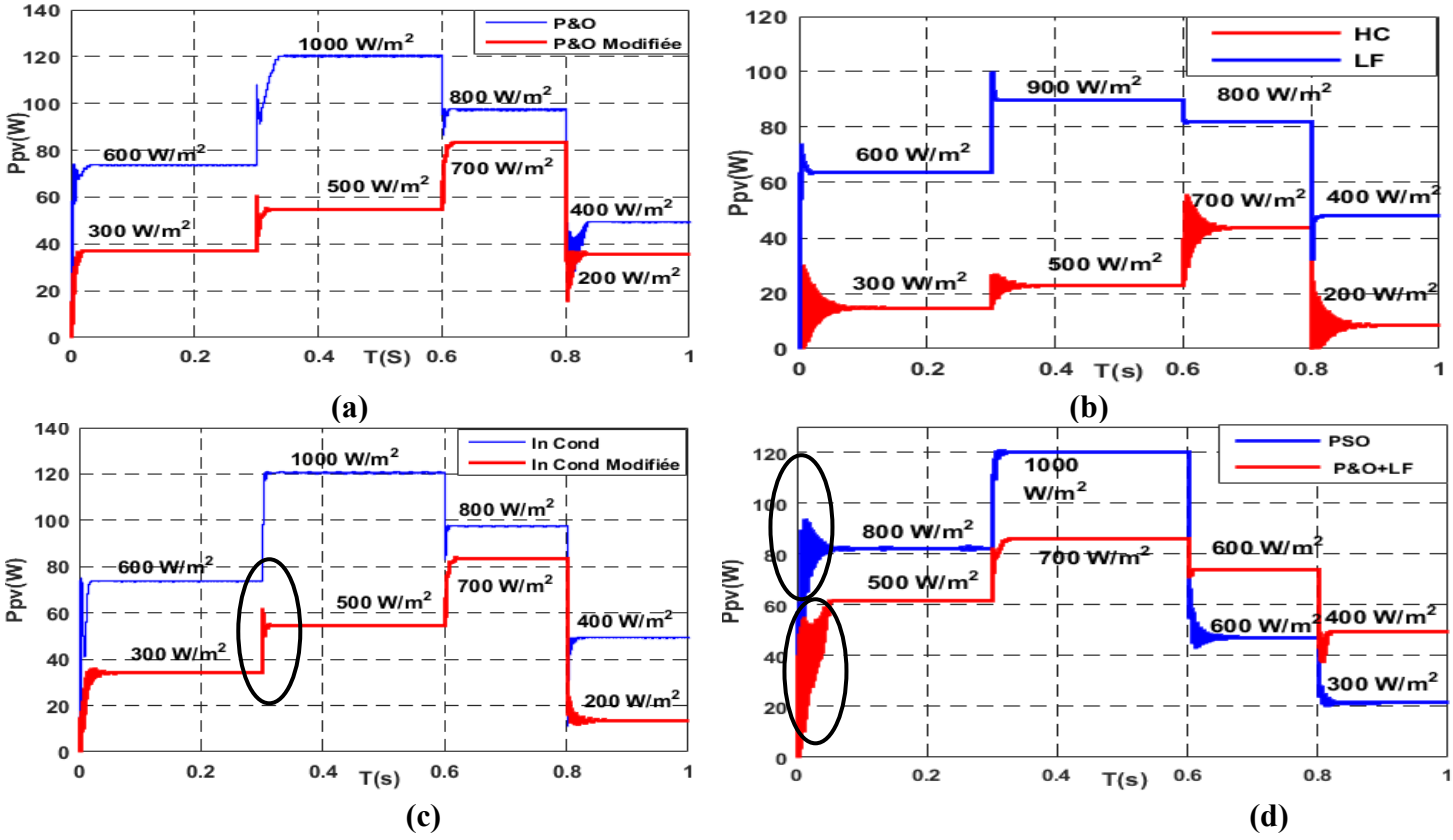


Figure 8. PV power of different MPPTs methods: a) P&O and In Cond methods; b) P&O and modified In Cond; c) HC and LF; d) PSO and P&O_LF.

4.2 EXPERIMENTAL RESULTS

To test the MPPT methods under CIUs, experiments were conducted on three BP Solar 60 W PV modules connected in series. The hardware implementation platform shown in Figure .5 was designed at the Relab. The measured characteristics of PV voltage, current, and power are given in Figure 10-

a-b-c-d-e-f. The experimental conditions were conducted under ambient temperatures ranging between 25 °C and 28 °C, with irradiance levels varying between approximately 200 W/m² and 800 W/m² depending on weather conditions and shading adjustments

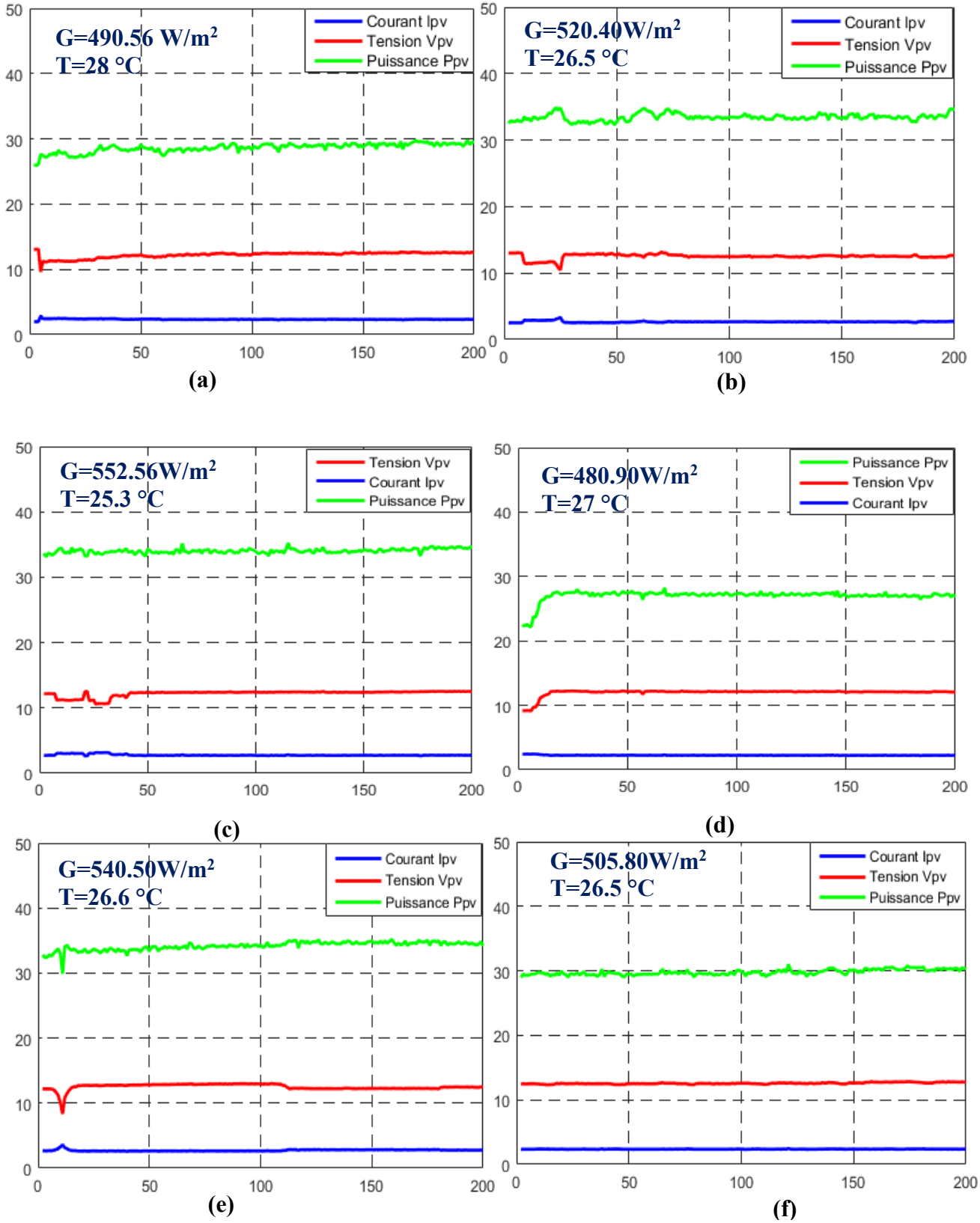


Figure 9. Experimental power, current and voltage curves of different MPPT methods:

(a)P&O, (b)InCond, (c) HC, (d) FL(e) FL_P&o (f) PSO.

Table 4. Comparative evaluation of different MPPT methods.

MPPTs Methods	Irradiation W/m² Temperature °C	Convergence time(ms)	Efficiency %	Average Power(W)	Used sensors	Ability to track under COP	Oscillation at PPM
P&O	490.56 28.00	05.00	94.93	28.5250	V, I	No	Exists
InCond	520.40 26.50	25.00	95,99	33.4852	V, I	No	Exists
HC	552.56 25.30	24.00	99.40	34.0394	V, I	No	Exists
LF	480.90 27.00	10.00	97.13	34.1784	V, I	Yes	Exists
LF_ P&O	540.5 26.6	5.500	96.15	29.8037	V, I	Yes	Exists
PSO	505.80 26.50	03.30	95.73	27.0304	V, I	Yes	Exists

Under constant temperature (25 °C) and uniform irradiation, all MPPT methods were able to track the maximum power point. However, clear differences in dynamic behavior and stability were observed. The P&O method exhibited the slowest convergence time, reaching steady state after approximately 0.05 s, whereas the other techniques converged faster, within about 0.03 s. This slower response is mainly attributed to the fixed perturbation step size of the conventional P&O algorithm, which limits its ability to rapidly reach the MPP. The modified version of the P&O algorithm introduces an adaptive perturbation step size that decreases as the operating point approaches the MPP, thereby reducing steady-state oscillations while maintaining fast convergence. In contrast, the conventional P&O uses a fixed perturbation step. Similarly, the modified Incremental Conductance algorithm incorporates an adaptive decision threshold and variable duty cycle adjustment to improve stability and tracking accuracy under rapidly varying irradiation conditions.

Moreover, noticeable oscillations in PV voltage, current, and output power were observed for the P&O and InCond methods. These oscillations around the peak power point reduce the effective harvested energy and indicate lower steady-state efficiency. In contrast, methods such as HC, LF, PSO, and the adaptive P&O_LF demonstrated reduced oscillations and improved stability, confirming their superior tracking precision under steady environmental conditions.

When irradiation levels were varied while maintaining constant temperature, the performance differences among the MPPT methods became more pronounced. The HC method showed a slower

dynamic response and significant oscillations around the MPP, particularly at low irradiation levels (200 W/m²). This behavior highlights the sensitivity of hill-climbing approaches to rapid environmental changes and reduced irradiance. The LF-based method, however, demonstrated a much faster response and minimal oscillations during irradiation transitions. This confirms its ability to adapt efficiently to dynamic operating conditions. Similarly, the PSO and P&O_LF methods showed fast convergence following irradiation changes, although initial oscillations were observed during the MPP search phase. Despite this, their overall tracking speed and accuracy were superior to conventional algorithms.

5. Conclusion

In this paper, we have presented the results of our simulation and experimental implementation of Maximum Power Point Tracking (MPPT) methods under Uniform Irradiance Conditions (UICs) and variations in irradiation levels. The results are divided into two parts. The first part includes various simulations using the MATLAB/Simulink software under different conditions, specifically: uniform irradiance conditions and rapidly varying atmospheric conditions. The second part comprises the validation of different MPPT methods implemented experimentally and the simulation of MPPT methods, including the Perturb and Observe method (P&O), modified P&O method, Incremental Conductance method (InCond), modified (improved) InCond method, Hill Climbing method (HC), Fuzzy Logic-based (FL) method, Adaptive P&O_FL method, and Particle Swarm Optimization method (PSO). The flexibility and comparison of the MPPT methods have been tested.

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Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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