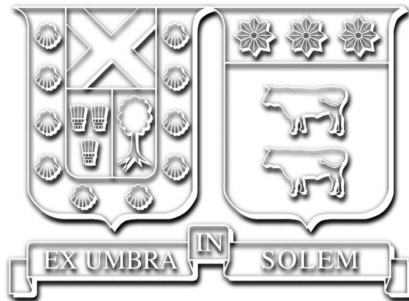




Implementación experimental de un algoritmo de control RPPT robusto frente a irradiancia variable y sombreado parcial en plantas fotovoltaicas conectadas a red

BASTIÁN OSVALDO BÓRQUEZ CARRASCO

2026

Requisito parcial para obtener el título de:
Ingeniero Civil Electricista

Profesor Guía:
Dr. Johnny Rengifo Santana (UTFSM)

Profesor Patrocinante:
Dr. Antonio Sanchez Squella (UTFSM)

Profesor Co-Referente:
Ing. Ignacio Jara Pavez (UTFSM)

Santiago, 03 de Septiembre de 2026.



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Tipo de monografía (marcar una opción): ☒ Memoria o trabajo de título ☐ Tesis de Postgrado
Implementación experimental de un algoritmo de control RPPT robusto frente a irradiancia variable y

Título del trabajo: sombreado parcial en plantas fotovoltaicas conectadas a red

Nombre del candidato(a): Bastían Osvaldo Bórquez Carrasco

Carrera / Grado: Ingeniería Civil Eléctrica

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Adaptive RPPT-MPC for Grid-Connected PV Systems with GMPP Estimation under Dynamic Irradiance and Partial Shading Conditions

Abstract—Photovoltaic generation in modern power systems requires more flexible control solutions that allow not only maximum energy extraction but also the provision of ancillary services through active management of power reserves. This work presents a new Reserve Power Point Tracking (RPPT) algorithm for grid-connected photovoltaic systems, based on model predictive control (MPC) and adaptive global maximum power point (GMPP) estimation without requiring environmental sensors. The proposed approach integrates a lightweight operational dynamics observer to detect relevant changes in operating conditions, enabling the activation of voltage-sweep-based GMPP estimation routines only when necessary. In this way, unnecessary voltage sweeps and the associated power disturbances and computational effort are reduced, even under partial shading conditions (PSC). The proposed algorithm is validated through a controlled simulation case in MATLAB/Simulink and experimental tests under real environmental and grid conditions. The results demonstrate the functionality and adaptability of the proposed scheme under changes in power reserve requirements, irradiance variations, and partial shading, by determining the photovoltaic array voltage reference according to the required power reserve.

Index Terms—Reserve power point tracking (RPPT), global maximum power point (GMPP), partial shading conditions (PSC), photovoltaic systems (PV), model predictive control (MPC).

I. INTRODUCTION

THE global commitment to achieving carbon neutrality by 2050 has led to a substantial increase in the deployment of photovoltaic (PV) power plants. As a result, solar energy penetration in electric power systems (EPSs) has increased significantly, leading to a reduction in the operation of conventional fossil-fuel-based generators, which contribute to power system robustness through rotational inertia. This scenario is particularly relevant in countries such as Chile, where the exceptional availability of solar resources, together with the sustained reduction in photovoltaic module costs and the progressive increase in their efficiency, has driven a rapid expansion of PV generation. Consequently, research and development of new PV control strategies have been promoted to enhance grid security through voltage regulation, frequency control, and power management [1].

Traditionally, the main objective of PV control has been to maximize the generated power. For this purpose, algorithms have been developed to track the maximum power point of the P–V curve (MPPT) [2], [3]. Under uniform irradiance conditions, the P–V curve is generally unimodal and therefore exhibits a unique maximum power point (MPP), whose location varies with irradiance and temperature. In contrast, under nonuniform irradiance conditions, such as PSC, the P–V curve may exhibit multiple local maxima. For this reason, advanced methods and improved MPPT variants have been developed to identify the GMPP [4]–[7].

Currently, PV control strategies focused exclusively on maximum power extraction are no longer sufficient. Modern power systems require PV systems to participate in ancillary services, which demands the capability to track dynamic power generation setpoints and maintain active power reserves. These functionalities enable effective control of the output power, allowing the PV system to respond to both upward and downward power adjustments required by the grid [8].

Two main strategies have been identified to enable the retention of active power reserves. The first is through the use of energy storage systems (ESSs), which, although they provide flexibility, also increase the complexity of power systems and integration costs [9]–[12]. The second is flexible power point tracking (FPPT), which deliberately limits power generation by operating the PV system below the MPP. This strategy enables the maintenance of internal power reserves and compliance with active power setpoints without requiring external energy storage, thereby allowing the implementation of key functionalities such as stable power supply and dynamic response to grid fluctuations, while maintaining its effectiveness even under partial shading conditions [13], [14].

FPPT algorithms enable PV systems to operate below the MPP while tracking active power setpoints, and have proven to be effective methods for limiting injected power while providing an adequate dynamic response [15]–[21]. However, these algorithms are not designed to estimate the maximum available power in real time, even though this information is essential for accurately determining the power reserve, defined as the difference between the maximum power point and the operating point. Since the MPP continuously varies with environmental conditions, its real-time estimation is fundamental for implementing reserve-based control strategies, such as frequency support or optimized energy storage management.

The lack of visibility of the maximum power point limits the use of FPPT as a comprehensive energy control tool. Therefore, an approach is required that combines active power setpoint tracking with real-time estimation of the maximum power point, thereby enabling more flexible, robust, and adaptive management in response to the dynamic requirements of modern power systems.

Based on this requirement, RPPT emerges as an alternative approach to address the aforementioned limitations. Similar to FPPT, this strategy enables operation according to power setpoints below the maximum power point; however, it differs in that it can also estimate the maximum power point in real time. This capability enables explicit and reliable management of the power reserves available from the PV system, thereby facilitating its participation in ancillary services. Previous studies have proposed different RPPT strategies that combine maximum power point estimation with power setpoint tracking

using direct and indirect measurement techniques, system modeling, or hybrid models [22].

The work presented in [8] proposes a power reserve control strategy for two-stage PV systems designed without the use of external sensors, providing a lower-cost and simpler implementation alternative. The approach combines switching between a fast-response MPPT algorithm and a constant power generation (CPG) scheme, enabling both power estimation and power limitation. However, this approach is restricted to operation at only one point around the maximum power point and does not consider partial shading conditions or GMPP detection, which can affect the accuracy of power reserve control.

In [23], a Delta Power Control (DPC) strategy is proposed for multistring PV systems. The strategy consists of operating one of the strings in MPPT mode to estimate the total available power, while the remaining strings operate in CPG mode. This approach does not require external sensors or energy storage elements, resulting in a more cost-effective design. However, the proposed strategy assumes uniform irradiance among the strings and does not consider scenarios with multiple power maxima under partial shading conditions, which limits its applicability under real operating conditions.

In [24], a power reserve control strategy is proposed for two-stage systems based on a diode model that is adjusted in real time to estimate the maximum power point without requiring external sensors. This method is characterized by its accuracy and robustness against disturbances and rapid irradiance variations. Nevertheless, its performance is limited because it assumes uniform operating conditions and therefore does not consider partial shading scenarios or GMPP detection, similarly to the previous method.

In contrast to the previous works, [25] presents a fast active power control strategy combined with a maximum power point estimator, both of which rely on irradiance and temperature sensors, as well as technical information. This strategy achieves fast responses on the order of milliseconds to frequency disturbances without requiring energy storage. However, it is limited by its dependence on external sensors and the assumption of uniform irradiance, which restricts its applicability under partial shading conditions that are neither considered nor detected.

According to [26], MPP estimation is performed using a least-squares fitting method applied to data obtained by inducing a voltage ripple. Although this technique enables operation with power reserves without requiring environmental sensors, its effectiveness depends on the quality and consistency of the induced voltage ripple, as well as on the selective execution of a full P–V curve sweep, which is only triggered when the magnitude of the shading exceeds a predefined threshold. This dependence limits the system response under dynamic conditions in which irradiance changes rapidly without modifying the shading pattern. Such a limitation may delay MPP updating and negatively affect the accuracy of power reserve management.

In [27], a power setpoint tracking algorithm is proposed that integrates maximum power point estimation with a flexible control strategy through nonlinear fitting of the PV model

using the Levenberg–Marquardt algorithm. This approach is characterized by not requiring environmental sensors, providing high accuracy under steady operating conditions, and being compatible with RST and P&O methods. In addition, the use of decoupled time loops allows the computational burden to be managed. However, the high computational requirements represent a challenge for implementation in embedded systems. Moreover, by assuming a unimodal P–V curve, the method lacks the capability to detect or track the GMPP under partial shading conditions. Furthermore, the reliability of the fitting process is highly dependent on the quality of the measurement window, whose update frequency is limited.

In [22], a Dynamic Reserve Power Point Tracking (DRPPT) scheme is described. This approach performs a continuous voltage sweep between two predefined values to estimate the MPP and regulate the delivered power, without requiring sensors or generator models. Although this method stands out for its simplicity and its ability to operate in MPPT, RPPT, and FPPT modes, the continuous execution of the sweep produces periodic power oscillations that deteriorate power quality and increase the stress on the DC-link. In addition, the method does not include mechanisms to detect changes in the PV generator operating conditions during the sweep, which implies assuming that the GMPP lies within the explored voltage range. This represents a critical limitation under dynamic irradiance or partial shading conditions. It is also important to note that the experimental validation in this work was carried out at low power (20 W), and therefore the impact of the periodic voltage sweeps on power quality and DC-link dynamics in higher-power grid-connected systems remains to be assessed.

More recently, [28] proposes a Q-learning-based GFPPT strategy for regulating photovoltaic power under partial shading conditions, considering both absolute power references and reserves defined with respect to the GMPP. Although learning during operation progressively reduces the convergence time, the discretization of the state and action spaces increases processing, memory, and implementation requirements compared with deterministic methods. In addition, the strategy was validated using a low-power prototype consisting of four 20 W modules connected to a battery bank, without grid connection. Therefore, its scalability and performance in higher-power, grid-connected photovoltaic systems still need to be assessed.

Finally, [29] proposes a power reserve control strategy for large-scale photovoltaic plants based on reference inverters. Selected units operate in MPPT mode, and their power measurements are used to estimate the maximum available power of other units operating under FPPT. Although the method avoids environmental sensors and complex photovoltaic models, its accuracy depends on the similarity of irradiance conditions among the units and may therefore deteriorate under heterogeneous shading or rapid cloud-induced variations. Moreover, it does not directly identify the GMPP by exploring the P–V curve, and its performance is validated only through simulations, without considering the non-idealities associated with an experimental implementation.

In this context, this work proposes the experimental implementation of an RPPT algorithm for grid-connected photo-

voltaic plants, aimed at overcoming the limitations identified above. On the one hand, approaches that assume uniform environmental conditions or depend on external sensors are unable to locate the GMPP under partial shading or rapid irradiance transitions. On the other hand, methods based on complex search algorithms improve GMPP identification but require a high computational burden, which complicates their real-time implementation. Likewise, procedures based on continuous voltage sweeps rely on fixed intervals that do not guarantee proper GMPP capture under dynamic irradiance conditions, generate significant power ripple, and increase the stress on the DC-link.

In response to these limitations, the proposed approach combines principles of MPC with an adaptive GMPP estimation architecture capable of adjusting to rapid changes in operating conditions. This eliminates the need for irradiance and temperature sensors while avoiding unnecessary P–V curve sweeps. The proposed approach aims to achieve stable and efficient operation even under variable irradiance or partial shading conditions, providing a robust and feasible alternative for the control of grid-connected photovoltaic plants. Specifically, the RPPT algorithm considers:

- The module referred to as the photovoltaic generator operational dynamics observer incorporates a simplified monitoring strategy that does not require environmental sensors and is designed to continuously analyze power and current fluctuations. This monitoring facilitates the identification of irregularities in the operating conditions, such as transients caused by atmospheric changes, significant irradiance variations, or partial shading conditions. This capability enables the system to determine whether the voltage sweep procedure needs to be activated for GMPP localization.
- The GMPP estimation strategy dynamically adapts to the operating state of the PV generator. As long as the observer does not detect relevant changes in the operating conditions, the previously determined operating point is maintained without executing unnecessary additional voltage sweeps, thereby reducing the computational burden and the associated disturbances. Conversely, when the observer detects significant changes in the operating conditions, a specific extended-sweep routine is executed to locate the GMPP and determine the new operating point.
- The predictive controller evaluates a discrete set of candidate voltages after each sweep. The candidate is selected by minimizing a cost function that penalizes the deviation between the candidate voltage and the target voltage, as well as the deviation between the predicted power and the power reference. In this way, the new operating point of the system is determined.

The proposed algorithm is validated through simulation and experimental tests, with the latter conducted under real environmental and grid conditions, without relying on photovoltaic or grid emulators. This enables the overall functionality and adaptability of the proposed strategy to be evaluated.

TABLE I
PARAMETERS OF THE EXPERIMENTAL SETUP.

Subsystem	Parameter	Value
Buck converter	Capacitance	4400 μF
Buck converter	Inductance	9 mH
Buck converter	Resistance	20 m Ω
AFE DC link	Capacitance	3300 μF
RL filter	Inductance	1.5 mH
RL filter	Resistance	20 m Ω
Three-phase grid	Line-to-line voltage	80 V
Control platform	Control frequency	10 kHz

II. METHODOLOGY

This section presents the methodology developed for the implementation of the proposed RPPT algorithm. First, the architecture of the grid-connected photovoltaic system is described. Second, the operating principles and main stages of the proposed RPPT algorithm are detailed. Third, the tests used to evaluate the proposed algorithm are described.

A. System architecture

The proposed algorithm is implemented in a two-stage grid-connected photovoltaic system (Fig. 1). This architecture is commonly employed in grid-tied applications due to its ability to decouple the control of the PV generator from the control of power injection. The system consists of a photovoltaic array composed of three series-connected modules coupled to a DC–DC buck converter and a DC–AC AFE inverter connected to an RL filter and a three-phase grid. Both converters are coupled via a DC-link with an intermediate capacitor that acts as an energy buffer. The main electrical parameters of the experimental setup are presented in Table I, while the characteristics of the photovoltaic modules are summarized in Table II.

Both the DC–DC converter and the inverter are controlled through conventional PI-based control loops. The control loop of the DC–DC converter adjusts the operating point of the PV generator by tracking the voltage reference (V_{ref}), determined by the proposed RPPT algorithm. The inverter, in turn, is responsible for maintaining a constant DC-link voltage and injecting into the grid the power extracted from the PV generator. The control strategy is implemented using a dSPACE MicroLabBox platform.

The system provides dynamic support capabilities by tracking an active power setpoint. This enables the system to maintain power reserves that can be used as an operational resource for ancillary services, providing a flexible response to power-system requirements. The proposed algorithm assumes availability of voltage and current measurements from the PV generator (V_{pv} , I_{pv}), without requiring irradiance or temperature sensors.

B. Proposed RPPT algorithm

The general flow of the proposed RPPT algorithm is shown in Fig. 2. The algorithm comprises three main processes: adaptive GMPP estimation, RPPT operation using MPC, and operating-condition change detection and sweep activation. These processes are described in the following subsections.

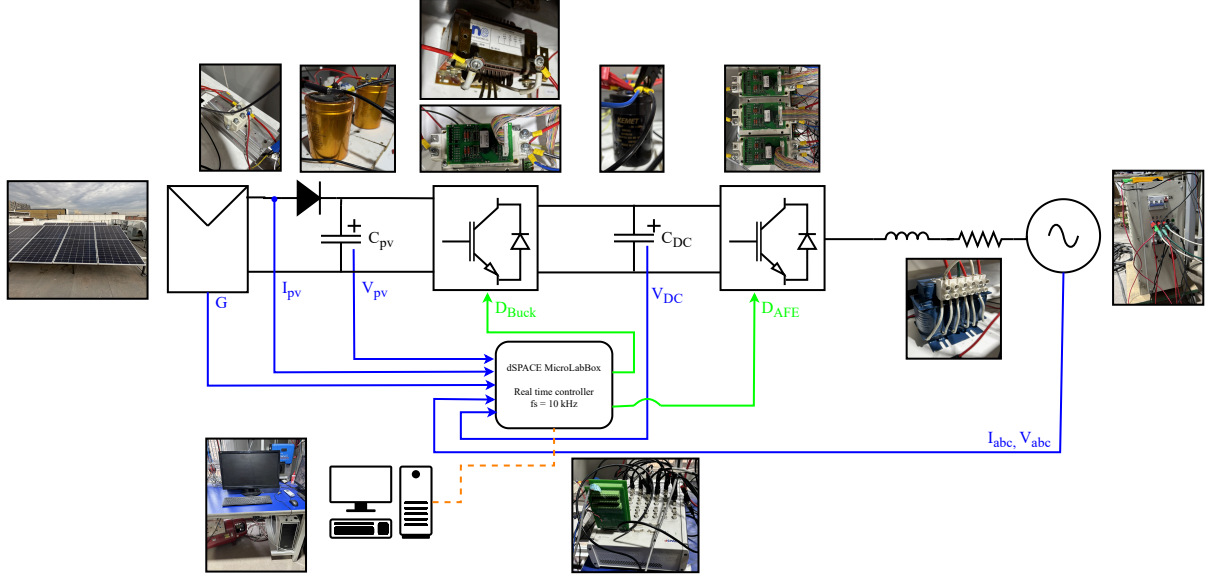


Fig. 1. Architecture of the grid-connected photovoltaic system.

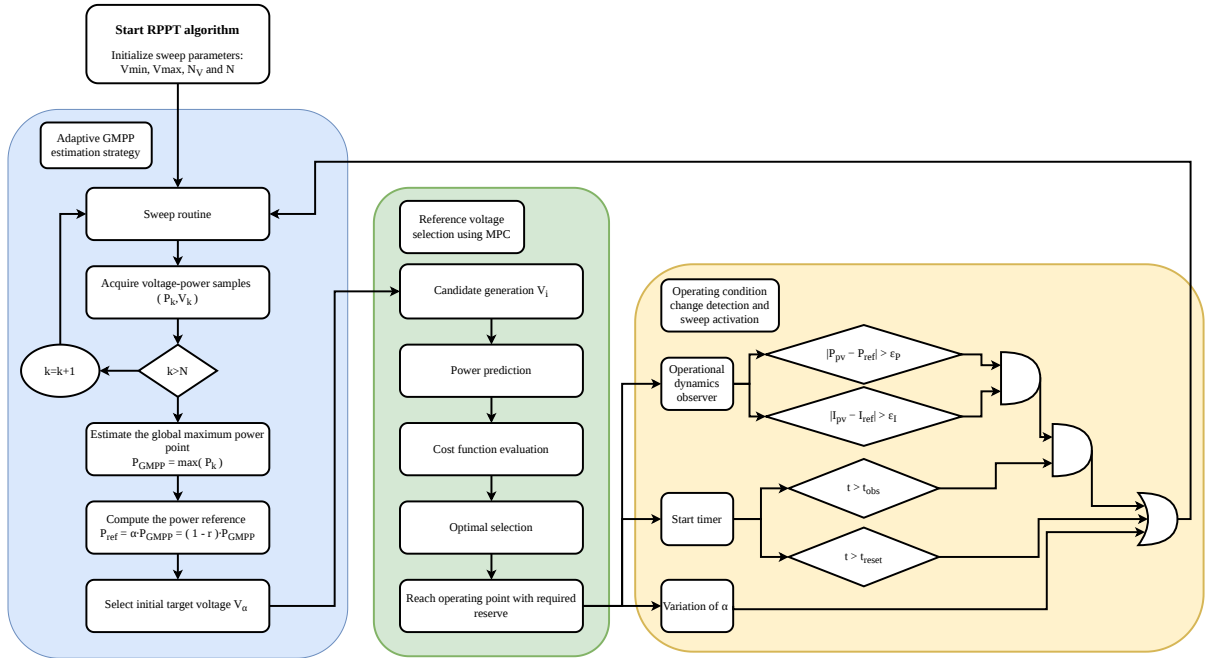


Fig. 2. General structure for RPPT control.

1) **Adaptive GMPP estimation strategy:** The proposed strategy alternates between operation without sweep and sweep-based GMPP estimation. A voltage sweep is executed at algorithm startup, whenever the required power reserve level is modified, or when the operational dynamics observer detects a relevant change in the operating conditions. In the absence of these events, the previously determined operating point is maintained without performing additional sweeps.

1) **Operation without sweep:** An operating point defined by the required power reserve and the corresponding voltage is established. This point remains unchanged

until a disturbance triggers a new sweep.

2) **Sweep routine for GMPP estimation:** To perform the voltage sweep of the P-V curve of the PV array, four parameters are defined: V_{min} , V_{max} , N_V and N , representing the lower voltage limit, the upper voltage limit, the number of voltage levels used to construct each ramp, and the total number of measurements, respectively.

Once the need to execute a sweep is detected, the voltage reference of the PV array is modified through a sequence composed of three stages. In the first stage,

TABLE II
FLASH-TEST CHARACTERISTICS OF THE THREE PV MODULES UNDER
STC CONDITIONS ($G=1000 \text{ W m}^{-2}$, $T=25^\circ \text{C}$).

Parameter	Module 1	Module 2	Module 3
Manufacturer	Anhui Sine New Energy Co., Ltd.		
Model	SN540-144M		
Number of cells	144	144	144
P_{mp} W	523.81	521.29	521.16
V_{oc} V	49.338	49.358	49.323
I_{sc} A	13.547	13.492	13.475
V_{mp} V	40.659	40.618	40.713
I_{mp} A	12.883	12.834	12.801
$\alpha_{V_{oc}}$ $\% ^\circ \text{C}^{-1}$	-0.1272	-0.1250	-0.1247
$\alpha_{I_{sc}}$ $\% ^\circ \text{C}^{-1}$	0.0037	0.0033	0.0047

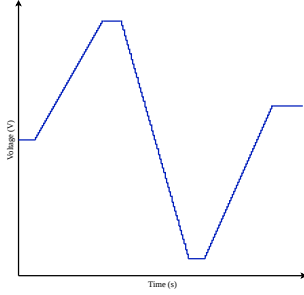


Fig. 3. Voltage reference waveform during the sweep.

the voltage is progressively increased from the measured value (V_{med}) to the upper limit of the sweep. In the second stage, the reference is maintained at the upper limit for a predefined interval. In the third stage, the voltage is decreased from the upper to the lower limit of the sweep. The voltage-reference sequence associated with the ascending ramp, holding stage, and descending ramp is described by Eq. (1):

$$\begin{aligned}
 V_k^\uparrow &= V_{med} + \frac{k-1}{N_V-1} (V_{max} - V_{med}), \\
 V^\rightarrow &= V_{max}, \\
 V_k^\downarrow &= V_{max} + \frac{k-1}{N_V-1} (V_{min} - V_{max}),
 \end{aligned} \quad k = 1, \dots, N_V. \quad (1)$$

where N_V denotes the number of voltage levels used to construct each ramp.

During the ascending and descending ramps, the measured voltage and power values of the PV array are periodically stored. In this way, N pairs of measurements are obtained, allowing the P-V curve to be reconstructed within the explored voltage range. The applied voltage-reference sequence is shown in Fig. 3.

Once sample acquisition is complete, the global maximum power point is identified as the operating point associated with the highest power value recorded during the sweep. This criterion relies on a direct comparison of all measured power values and is particularly suitable under partial shading conditions, since the P-V curve may exhibit several local maxima.

2) **Voltage reference selection using MPC:** Model Predictive Control is used after each voltage sweep to determine the voltage reference to be applied to the DC-DC converter according to the required power reserve. The controller operates in discrete time with a one-step prediction horizon, evaluating a finite set of candidate voltages through a predictive model and a cost function. The procedure is described as follows:

- 1) **Power reference:** The reference power is calculated according to the required power reserve level as:

$$P_{ref} = (1 - r) \cdot P_{GMPP} = \alpha \cdot P_{GMPP} \quad (2)$$

where r represents the power reserve coefficient and $\alpha = 1 - r$ is the power reference coefficient. The reserved power is then defined as:

$$P_{res} = P_{GMPP} - P_{ref} \quad (3)$$

- 2) **Candidate generation:** An initial target voltage (V_α) is selected from the measurements stored during the voltage sweep. This voltage corresponds to the sampled operating point whose power is closest to P_{ref} . A finite set of candidate voltages V_i is then generated within a predefined range. If the difference between V_{med} and V_α exceeds a predefined threshold, the candidate set is centered on V_α . Otherwise, it is centered on V_{med} , thereby enabling local adjustments around the current operating point. This finite set defines the admissible control actions evaluated by the controller.
- 3) **Power prediction:** The five samples stored during the voltage sweep with voltage values closest to V_α are selected. These samples are used to obtain a local quadratic approximation of the P-V curve through a least-squares fit:

$$\hat{P}(V) = aV^2 + bV + c. \quad (4)$$

Once the coefficients a , b , and c are obtained, the predicted power ($\hat{P}_i$) is computed for each candidate voltage V_i .

- 4) **Cost function evaluation:** A cost function, $J(V_i)$, is evaluated for each candidate voltage in order to balance power-reference tracking and voltage deviation:

$$J(V_i) = w_1 (\hat{P}_i - P_{ref})^2 + w_2 (V_i - V_\alpha)^2 \quad (5)$$

where w_1 and w_2 are weighting factors that balance the two control objectives. The coefficient w_1 penalizes deviations between the predicted power and P_{ref} , whereas w_2 penalizes deviations of the candidate voltage from V_α . Therefore, a larger w_1 prioritizes power-reference tracking, while a larger w_2 favors candidate voltages closer to the initial target voltage.

- 5) **Optimal selection:** The voltage reference V_{ref} is chosen as the candidate V_i that minimizes the cost function $J(V_i)$:

$$V_{ref} = \arg \min_{V_i} J(V_i). \quad (6)$$

This approach enables the tracking of the required power reference while keeping the selected operating point close to the voltage region associated with P_{ref} . Once V_{ref} has

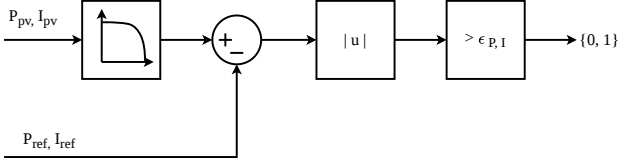


Fig. 4. Block diagram of the operational dynamics observer.

been determined, the operating voltage is gradually increased from $V_{\min}$ to V_{ref} through an additional voltage ramp. This transition limits abrupt variations in the PV-array voltage and, consequently, in the delivered power, thereby contributing to a stable transition toward the desired operating point.

3) *Operating condition change detection and sweep activation:* A mechanism for observing operational conditions is proposed, based on electrical measurements and without the need for environmental sensors. The implemented approach aims to identify in real time relevant transitions in the dynamics of the PV generator that justify executing a global sweep of the P–V curve to search for the GMPP.

The observer's logic is based on comparing the instantaneous power (P_{pv}) and current (I_{pv}) generated by the PV system with reference values associated with the last stable operating condition. These reference values, P_{ref} and I_{ref} , are updated after each GMPP estimation routine once the controller reaches the reserved power operating point. Then, the absolute deviations $|P_{pv} - P_{\text{ref}}|$ and $|I_{pv} - I_{\text{ref}}|$ are evaluated and compared with predefined thresholds ($\varepsilon_P, \varepsilon_I$), which delimit the acceptable variation range under normal operating conditions. This simultaneous evaluation reduces the observer's sensitivity to isolated fluctuations in either variable, thereby avoiding unnecessary voltage-sweep activations.

The observer state is represented by the Boolean variable S , defined as:

$$S = \begin{cases} 1, & \text{if } |P_{pv} - P_{\text{ref}}| > \varepsilon_P \quad \text{and} \quad |I_{pv} - I_{\text{ref}}| > \varepsilon_I \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

When $S = 1$, it is considered that there is a relevant disturbance in the operating condition of the PV generator, either due to irradiance variations, electrical mismatch, or other factors, activating the global scan mode of the algorithm to locate the GMPP. If $S = 0$, normal operation is maintained without additional sweeps. Fig. 4 illustrates the block diagram of the observer, which continuously compares the measured power and current with their corresponding stored reference values. The resulting absolute deviations are compared with the thresholds ε_P and ε_I , respectively. When both deviations exceed their corresponding thresholds, a mode change is triggered and a new voltage sweep is activated. The parameters of the proposed algorithm are presented in Table III.

After a voltage sweep is executed, a configurable timer establishes a minimum time interval before another sweep can be initiated. During this interval, the activation of additional sweeps is inhibited, preventing consecutive voltage scans from repeatedly perturbing the operating point of the PV array. Once the predefined interval has elapsed, sweep activation is enabled

TABLE III
PARAMETERS OF THE PROPOSED RPPT ALGORITHM.

Subsystem	Parameter	Value
Sweep routine	$V_{\min}$	20 V
Sweep routine	$V_{\max}$	142 V
Sweep routine	N_V	50
Sweep routine	N	50
Observer	ε_P	2 W
Observer	ε_I	0.5 A
MPC	w_1	0.1
MPC	w_2	0.01

again, and a new sweep can be executed if the power and current deviations exceed their corresponding thresholds. This mechanism contributes to maintaining stable system operation by avoiding excessively frequent sweeps.

C. Evaluation Scenarios for the Proposed Algorithm

The proposed algorithm is evaluated through one simulation case and four experimental cases, designed to assess different capabilities of the RPPT strategy. The considered cases are:

- 1) **Simulation case:** the overall operation of the proposed algorithm is evaluated in a controlled environment. For this purpose, the simulation is supplied with a variable irradiance profile and different modifications are introduced into the operating conditions. In addition, the algorithm is configured to operate only in the region corresponding to voltages below the voltage associated with the GMPP. Initially, the system operates in MPPT mode. Subsequently, the power reserve setpoint is established at 15%, following which a partial shading condition is introduced that reduces the irradiance applied to the third module to two-thirds of the irradiance of the remaining modules. Next, an irradiance variation is introduced to evaluate the observer response to changes in the operating conditions and, finally, the power reserve setpoint is increased to 30%. In this way, this scenario enables the joint evaluation of the algorithm response to setpoint changes and variations in operating conditions, under both uniform irradiance and partial shading conditions.
- 2) **Experimental case 1:** the operation of the proposed algorithm is evaluated under real operating conditions and partial shading. For this purpose, partial shading is applied according to the configuration shown in Fig. 5. The system initially operates in MPPT mode, after which the power reserve setpoint is successively changed to 25% and 50%.
- 3) **Experimental case 2:** the capability of the algorithm to deliberately select the operating region under real operating conditions is evaluated. Regions 1 and 2 are defined as those corresponding to operating voltages below and above the voltage associated with the GMPP, respectively. For this purpose, two independent tests are performed: in the first, the algorithm is configured to operate in region 1, whereas in the second, it is configured to operate in region 2. In both tests, the system initially operates in MPPT mode, after which the power reserve setpoint is established at 25%. In addition,



Fig. 5. Experimental photovoltaic array under partial shading.



Fig. 6. Experimental photovoltaic array under partial shading caused by adjacent structures.



Fig. 7. Experimental photovoltaic array without partial shading.

during these tests, the photovoltaic array is subjected to shading caused by adjacent structures, as shown in Fig. 6.

- 4) **Experimental case 3:** the adaptability of the algorithm to changes in the P–V characteristic of the photovoltaic array is evaluated. For this purpose, the system operates with a constant power reserve of 5% while the array transitions from a uniform irradiance condition, associated with a unimodal P–V curve, to a partial shading condition caused by adjacent structures, resulting in a multimodal characteristic.
- 5) **Experimental case 4:** the operation of the proposed algorithm is evaluated under real operating conditions and without partial shading. For this purpose, the power reserve setpoint is maintained constant at 25%. The photovoltaic array used in this test is shown in Fig. 7.

III. RESULTS AND DISCUSSION

The proposed RPPT algorithm is evaluated through simulation and experimental tests. The experimental validation is conducted under real environmental and grid conditions, using the setup shown in Fig. 1. The performance of the proposed strategy is assessed under the different operating scenarios described in Section II-C. During the experimental tests, the voltage, current, power, and irradiance of the photovoltaic array are recorded.

In the experimental results, P_{grid} is presented to illustrate the active power injected into the grid. The difference between P_{pv} and P_{grid} is mainly associated with the conversion losses, including switching and conduction losses, as well as losses in the passive components. For the experimental cases in which a model-based reference P–V characteristic is shown, this curve is obtained from a PV-array model parameterized using flash-test measurements of the experimental modules and configured to reproduce the corresponding shading conditions. This characteristic provides a reference for comparison with the P–V curve reconstructed during the voltage sweep.

During the experimental tests, the measured voltage follows the selected reference voltage after each sweep, while variations in measured power and current with respect to their stored reference values are used by the operational dynamics observer.

A. Simulation case

In this simulation test, the operation of the proposed algorithm is evaluated under controlled conditions. Fig. 8 shows the irradiance, power, current, and voltage of the photovoltaic array. Initially, the system operates in MPPT mode at an irradiance of approximately 530 W/m^2 , with a power reference of 845.7 W , a current reference of 7.02 A , and a voltage reference of 120.475 V . During the test, four variations of different origin significantly modify the operating conditions and trigger the execution of voltage sweeps.

The first sweep occurs at $t = 5 \text{ s}$, when the power reserve setpoint is established at 15%. From this sweep, the P–V curve shown in Fig. 8e is reconstructed, allowing the power reference to be updated to 718.1 W , the current reference to 7.174 A , and the voltage reference to 100.105 V . Subsequently, at $t = 9 \text{ s}$, the irradiance applied to the third module is reduced to two-thirds of the irradiance of the remaining modules. This modification produces a change in the operating conditions that is detected by the observer, triggering a second sweep, from which the P–V curve presented in Fig. 8f is reconstructed. In this second sweep, the algorithm updates the operating point to a power reference of 503.7 W , a current reference of 6.867 A , and a voltage reference of 73.285 V . In addition, at this point, the irradiance is approximately 520 W/m^2 .

Subsequently, at $t = 14.5 \text{ s}$, the decrease in irradiance to approximately 470 W/m^2 triggers a third sweep, from which the P–V curve presented in Fig. 8g is reconstructed. Based on this third sweep, the algorithm adjusts the power reference to 493.6 W , the current reference to 4.723 A , and the voltage reference to 104.5 V . After this sweep, the irradiance settles

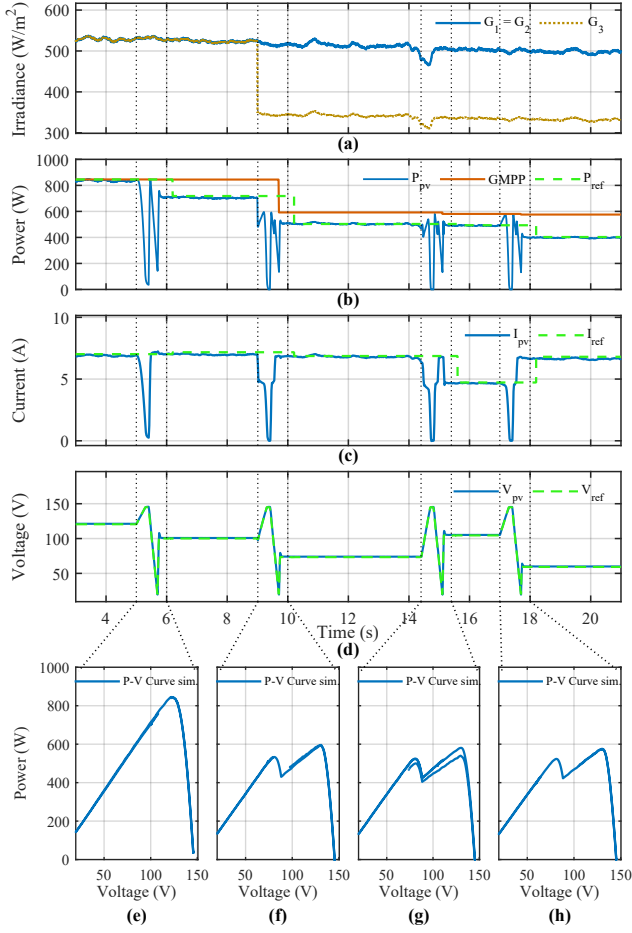


Fig. 8. Simulation results of the proposed algorithm: (a) Irradiance (G), (b) PV power (P_{pv}), power reference (P_{ref}) and GMPP, (c) PV current (I_{pv}) and current reference (I_{ref}), (d) PV voltage (V_{pv}) and voltage reference (V_{ref}), and (e)–(h) P–V curves obtained from the voltage sweeps.

at approximately 500 W/m^2 . It should be noted that, in the P–V curves reconstructed during the second and third sweeps, the same power setpoint can be achieved at different voltage levels. Since P_{ref} does not necessarily match one of the samples acquired during the sweep, the algorithm selects V_{α} as the voltage associated with the sampled power closest to P_{ref} . From this point, the set of control actions evaluated by the MPC is defined, and the voltage that minimizes the cost function is finally selected as V_{ref} .

Finally, at $t = 17 \text{ s}$, a change in the power reserve setpoint to 30% initiates a fourth sweep, from which the P–V curve presented in Fig. 8h is reconstructed. Based on this fourth sweep, the algorithm adjusts the power reference to 403 W, the current reference to 6.804 A, and the voltage reference to 59.227 V.

The simulation results show the behavior of the algorithm under different variations in the operating conditions, including changes in the power reserve setpoint, partial shading, and dynamic irradiance. In each case, the algorithm successfully identifies changes in the operating conditions, reconstructs the P–V curve, detects the new global maximum power point, and adjusts the system operating point around the established reference while considering the required power reserve. In this

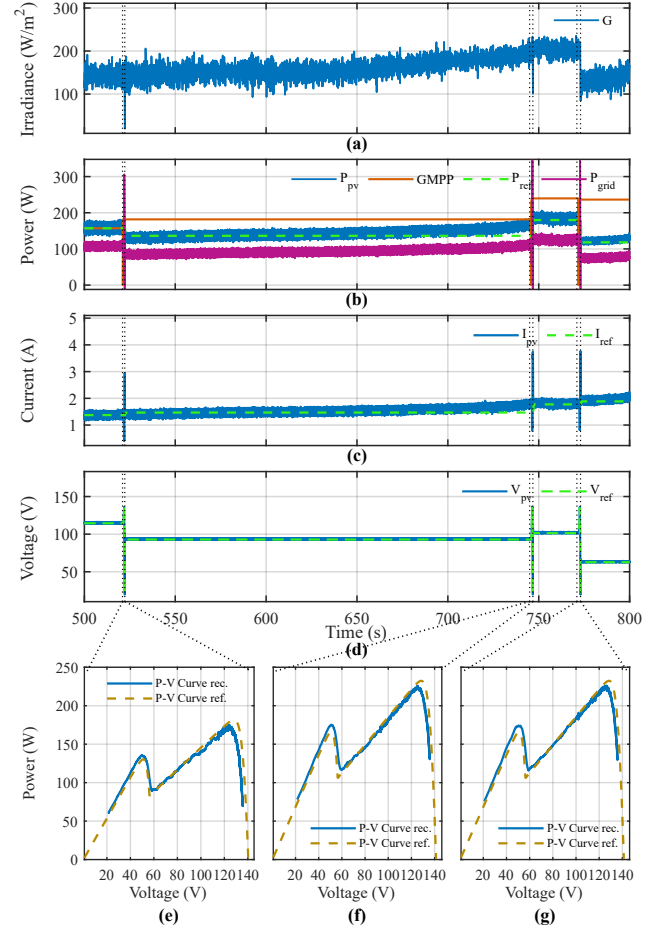


Fig. 9. Experimental results of the proposed algorithm under partial shading: (a) Irradiance (G), (b) PV power (P_{pv}), power reference (P_{ref}), GMPP, and grid power (P_{grid}), (c) PV current (I_{pv}) and current reference (I_{ref}), (d) PV voltage (V_{pv}) and voltage reference (V_{ref}), and (e)–(g) reconstructed and model-based reference P–V curves.

way, the overall operation of the proposed algorithm is verified under the controlled conditions considered in the simulation.

B. Experimental case 1

The proposed algorithm is evaluated during operation with different power reserve setpoints under partial shading conditions. Fig. 9 shows the measured irradiance, power, current, and voltage of the photovoltaic array. Initially, the system operates without power reserve at an irradiance of approximately 138 W/m^2 , with a power reference of 157.2 W, a current reference of 1.373 A, and a voltage reference of 114.482 V. During the test, three significant variations of different origin modify the operating conditions and trigger the execution of voltage sweeps.

The first sweep occurs at $t = 521 \text{ s}$, when the power reserve setpoint is set to 25%. From this sweep, the P–V curve shown in Fig. 9e is reconstructed, allowing the power reference to be updated to 136.3 W, the current reference to 1.468 A, and the voltage reference to 92.854 V. At $t = 745 \text{ s}$, the increase in irradiance to approximately 195 W/m^2 triggers a second sweep, from which the P–V curve presented in Fig. 9f is reconstructed. In this second sweep, the algorithm adjusts

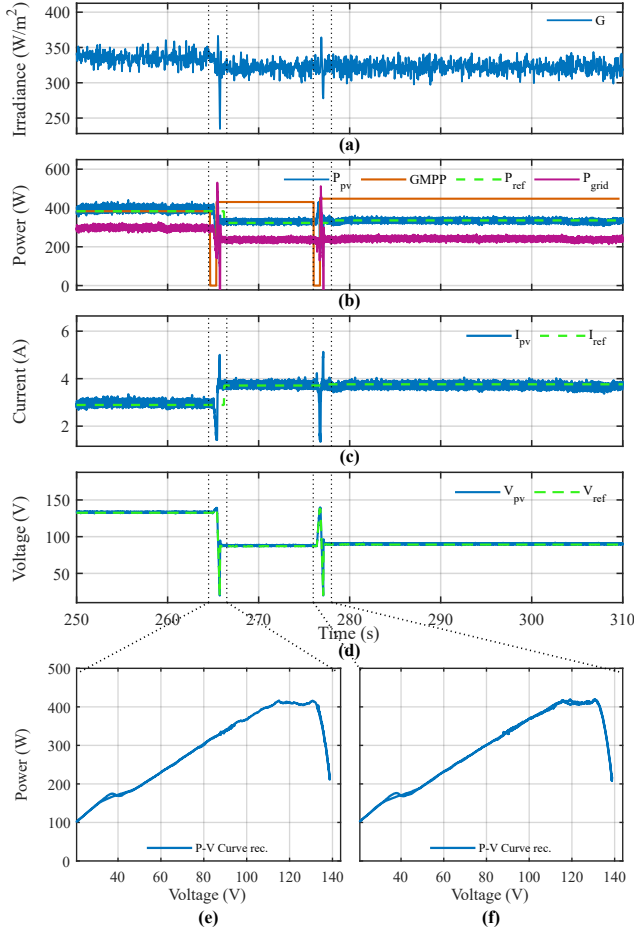


Fig. 10. Experimental results of the proposed algorithm operating in region 1: (a) Irradiance (G), (b) PV power (P_{pv}), power reference (P_{ref}), GMPP, and grid power (P_{grid}), (c) PV current (I_{pv}) and current reference (I_{ref}), (d) PV voltage (V_{pv}) and voltage reference (V_{ref}), and (e)–(f) P–V curves obtained from the voltage sweeps.

the operating point to a power reference of 179.8 W, a current reference of 1.774 A, and a voltage reference of 101.420 V. Finally, at $t = 771$ s, the power reserve setpoint is set to 50%, initiating a third sweep, from which the P–V curve shown in Fig. 9g is reconstructed. Based on this third sweep, the algorithm updates the power reference to 118.2 W, the current reference to 1.885 A, and the voltage reference to 62.704 V.

In the three sweeps, the algorithm successfully identifies changes in the operating conditions, reconstructs the P–V curve, detects the new global maximum power point, and adjusts the system operating point around the established reference while considering the required power reserve. In this way, the performance of the proposed algorithm is validated under partial shading conditions and with different power reserve setpoints.

C. Experimental case 2

In this case, the capability of the proposed algorithm to deliberately select the operating region of the P–V curve is evaluated. For this purpose, regions 1 and 2 are defined as the operating voltages below and above the voltage associated with the GMPP, respectively. One test is performed for each

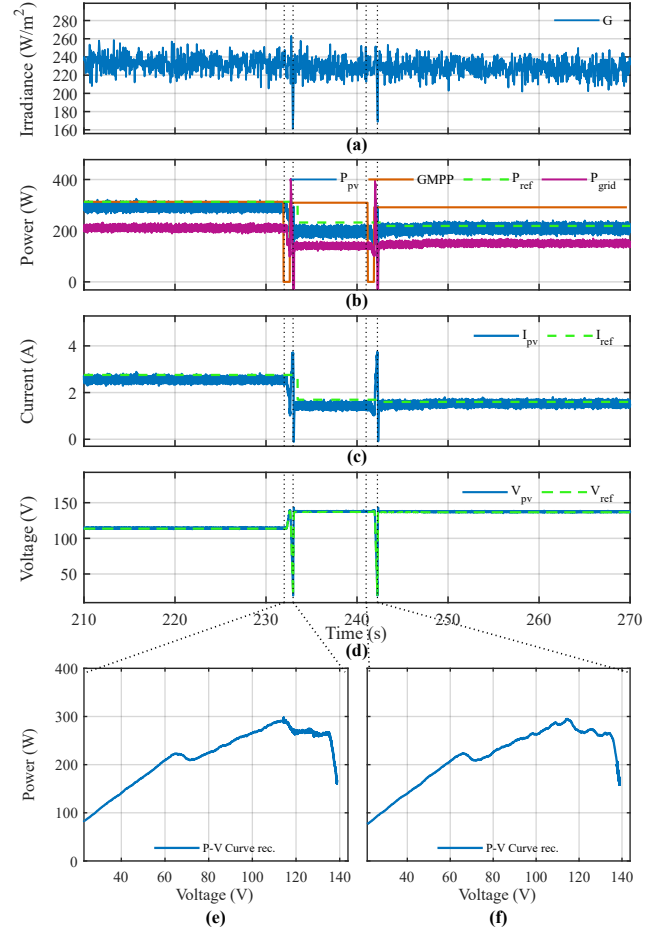


Fig. 11. Experimental results of the proposed algorithm operating in region 2: (a) Irradiance (G), (b) PV power (P_{pv}), power reference (P_{ref}), GMPP, and grid power (P_{grid}), (c) PV current (I_{pv}) and current reference (I_{ref}), (d) PV voltage (V_{pv}) and voltage reference (V_{ref}), and (e)–(f) P–V curves obtained from the voltage sweeps.

operating region, during which different variations in the operating conditions trigger the execution of voltage sweeps and the subsequent update of the operating point.

Fig. 10 shows the measured irradiance, power, current, and voltage of the photovoltaic array when the algorithm operates in region 1. Initially, the system operates without power reserve at an irradiance of approximately 340 W/m^2 , with a power reference of 395 W, a current reference of 2.982 A, and a voltage reference of 132.534 V. The first sweep occurs at $t = 264$ s, when the power reserve setpoint is established at 25%. From this sweep, the P–V curve shown in Fig. 10e is reconstructed, allowing the power reference to be updated to 323 W, the current reference to 3.711 A, and the voltage reference to 87.05 V. At $t = 276$ s, the decrease in irradiance to approximately 320 W/m^2 triggers a second sweep, from which the P–V curve presented in Fig. 10f is reconstructed. In this second sweep, the algorithm adjusts the operating point to a power reference of 335.8 W, a current reference of 3.762 A, and a voltage reference of 89.262 V. It can be observed that, after both sweeps, the operating voltage remains below the voltage associated with the GMPP, which is approximately 130.7 V.

Fig. 11 shows the measured irradiance, power, current, and voltage of the photovoltaic array when the algorithm operates in region 2. Initially, the system operates without power reserve at an irradiance of approximately 230 W/m^2 , with a power reference of 312.9 W , a current reference of 2.754 A , and a voltage reference of 113.589 V . The first sweep occurs at $t = 232 \text{ s}$, when the power reserve setpoint is established at 25%. From this sweep, the P-V curve shown in Fig. 11e is reconstructed, allowing the power reference to be updated to 232 W , the current reference to 1.693 A , and the voltage reference to 136.963 V . At $t = 241 \text{ s}$, the decrease in irradiance to approximately 220 W/m^2 triggers a second sweep, from which the P-V curve presented in Fig. 11f is reconstructed. In this second sweep, the algorithm adjusts the operating point to a power reference of 218.5 W , a current reference of 1.600 A , and a voltage reference of 136.603 V . It can be observed that, after both sweeps, the operating voltage remains above the voltage associated with the GMPP, which is approximately 114.2 V .

In both tests, the algorithm successfully identifies changes in the operating conditions, reconstructs the P-V curve, detects the new global maximum power point, and adjusts the system operating point around the established reference while considering both the power reserve and the operating-region constraint. In this way, the capability of the proposed algorithm to deliberately select the operating region according to the operator requirements is validated. In addition, when comparing both tests, it can be observed that operation in region 2 exhibits a deviation of power and current from their respective references between the first and second sweeps. This behavior is consistent with the higher sensitivity of region 2, where small irradiance variations can produce appreciable changes in power and current for a given operating voltage.

D. Experimental case 3

In this test, the proposed algorithm is evaluated during the transition from uniform irradiance conditions to partial shading conditions. Fig. 12 shows the measured irradiance, power, current, and voltage of the photovoltaic array. Initially, the system operates in MPPT mode at an irradiance of approximately 150 W/m^2 , with a power reference of 280.8 W , a current reference of 2.264 A , and a voltage reference of 124.061 V . During the test, multiple variations of different origin significantly modify the operating conditions and trigger the execution of voltage sweeps. Among the sweeps performed, four are selected to represent the evolution of the P-V curve from uniform irradiance to partial shading conditions.

The first sweep occurs at $t = 4 \text{ s}$, when the power reserve setpoint is established at 5%. From this sweep, the P-V curve shown in Fig. 12e is reconstructed, allowing the power reference to be updated to 260.2 W , the current reference to 2.063 A , and the voltage reference to 126.115 V . Then, at $t = 168 \text{ s}$, an increase in irradiance to approximately 250 W/m^2 triggers a second sweep, from which the P-V curve presented in Fig. 12f is reconstructed. In this second sweep, the algorithm updates the operating point to a power reference of 374.9 W , a current reference of 3.095 A , and a voltage reference of 121.119 V .

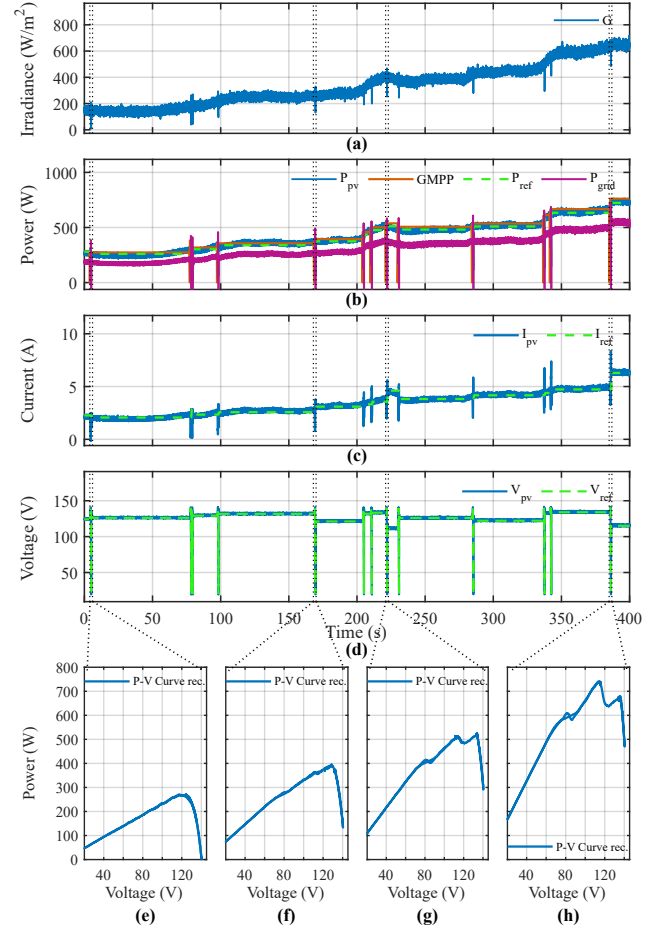


Fig. 12. Experimental results of the proposed algorithm with a 5% power reserve: (a) Irradiance (G), (b) PV power (P_{pv}), power reference (P_{ref}), GMPP, and grid power (P_{grid}), (c) PV current (I_{pv}) and current reference (I_{ref}), (d) PV voltage (V_{pv}) and voltage reference (V_{ref}), and (e)–(h) P-V curves obtained from the voltage sweeps.

Subsequently, at $t = 221 \text{ s}$, the increase in irradiance to approximately 380 W/m^2 triggers a third sweep, from which the P-V curve presented in Fig. 12g is reconstructed. Based on this third sweep, the algorithm adjusts the power reference to 511.1 W , the current reference to 4.608 A , and the voltage reference to 110.909 V . Finally, at $t = 385 \text{ s}$, an increase in irradiance to approximately 630 W/m^2 initiates a fourth sweep, from which the P-V curve presented in Fig. 12h is reconstructed. Based on this fourth sweep, the algorithm adjusts the power reference to 723.4 W , the current reference to 6.289 A , and the voltage reference to 115.027 V .

The selected sweeps show the evolution of the P-V characteristic from an initially unimodal curve under uniform irradiance conditions to a multimodal curve under partial shading. In each case, the algorithm successfully identifies changes in the operating conditions, reconstructs the P-V curve, detects the new global maximum power point, and adjusts the system operating point around the established reference while considering the required power reserve. These results demonstrate the capability of the proposed algorithm to adapt its operation when the PV array transitions from uniform irradiance to partial shading conditions.

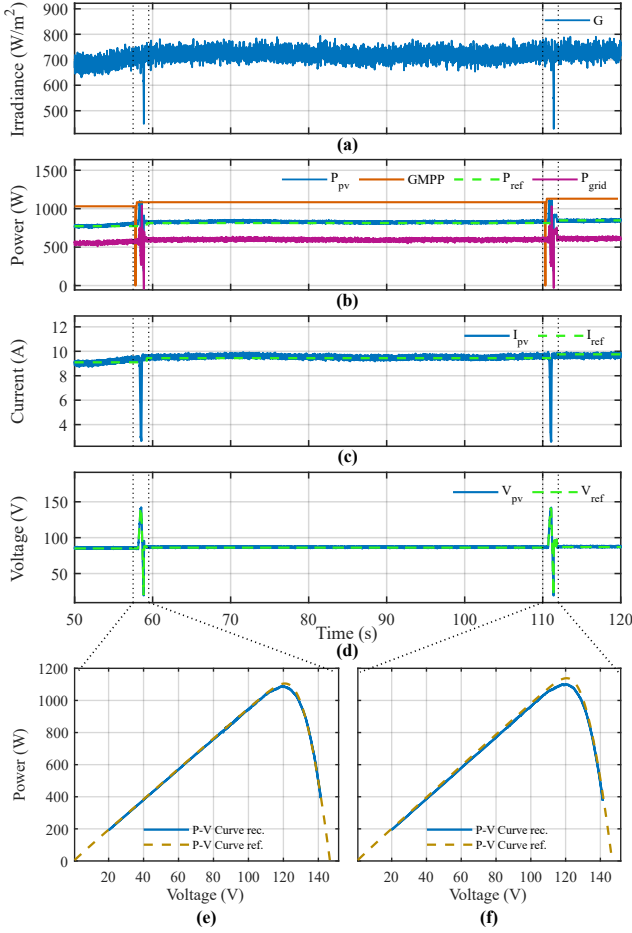


Fig. 13. Experimental results of the proposed algorithm with a 25% power reserve without partial shading: (a) Irradiance (G), (b) PV power (P_{pv}), power reference (P_{ref}), GMPP, and grid power (P_{grid}), (c) PV current (I_{pv}) and current reference (I_{ref}), (d) PV voltage (V_{pv}) and voltage reference (V_{ref}), and (e)–(f) reconstructed and model-based reference P–V curves.

E. Experimental case 4

The proposed algorithm is evaluated during operation with a 25% power reserve. Fig. 13 shows the measured irradiance, power, current, and voltage of the photovoltaic array. Initially, the system operates at an irradiance of approximately 680 W/m^2 , with a power reference of 773.4 W, a current reference of 9.1 A, and a voltage reference of 84.992 V. During the test, two significant variations in the operating conditions occur, which are detected by the observer and trigger the execution of voltage sweeps.

The first sweep occurs at $t = 57$ s, when the irradiance increases to approximately 710 W/m^2 , while the power and current reach 810.3 W and 9.581 A, respectively. From this sweep, the P–V curve shown in Fig. 13e is reconstructed, allowing the power reference to be updated to 813.2 W, the current reference to 9.443 A, and the voltage reference to 86.125 V. Subsequently, at $t = 110$ s, a further increase in irradiance to approximately 740 W/m^2 triggers a second sweep, from which the P–V curve presented in Fig. 13f is reconstructed. In this second sweep, the algorithm adjusts the operating point to a power reference of 847.5 W, a current reference of 9.752 A, and a voltage reference of 86.907 V.

In both sweeps, the algorithm successfully identifies changes in the operating conditions, reconstructs the P–V curve, detects the new global maximum power point, and adjusts the system operating point around the established reference while considering the required power reserve. In this way, the performance of the proposed algorithm is validated during RPPT operation with a 25% power reserve under uniform irradiance.

IV. CONCLUSION

An RPPT algorithm based on MPC was proposed for a grid-connected photovoltaic system. The proposed algorithm was evaluated through simulation and experimental tests, demonstrating its overall functionality and adaptability under different operating conditions. The results show that the strategy maintains robust operation under uniform irradiance conditions, dynamic irradiance variations, changes in the power reserve setpoint, and partial shading conditions. In addition, the capability of the algorithm to deliberately select the operating region with respect to the voltage associated with the GMPP was verified.

Based on the obtained results, it is demonstrated that the proposed algorithm enables power injection into the grid while maintaining an available power reserve, through GMPP estimation and the determination of an appropriate voltage reference for the photovoltaic array. In this way, the algorithm adapts the system operating point to different reserve requirements and environmental conditions without requiring irradiance or temperature sensors for its operation.

The main limitation of the proposed algorithm is associated with the operational dynamics observer, since its performance directly affects the adaptive activation of the GMPP estimation routine, which represents one of the key distinguishing features of the proposed algorithm. The sensitivity of the observer depends on both internal factors, such as the appropriate selection of the power and current deviation thresholds, and external factors, such as the quality and resolution of the measurement instruments. On the one hand, excessively relaxed thresholds may prevent gradual changes in operating conditions from being detected, delaying the activation of a new voltage sweep. On the other hand, overly strict thresholds, together with noisy or limited-resolution measurements, may result in false or excessively frequent sweep activations. Therefore, future work may consider adaptive threshold selection, additional filtering techniques, and/or alternative decision mechanisms, while preserving the proposed sensorless approach with respect to environmental measurements.

As future work, the developed algorithm is proposed to be integrated with a power control strategy that dynamically utilizes the available reserve for the provision of grid support services. In addition, the behavior of the algorithm should be evaluated through long-duration tests and on higher-power photovoltaic platforms, in order to assess its performance under more demanding operating conditions and scenarios closer to large-scale applications.

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