

Comparative Performance of PSO-MPPT and Conventional P&O-MPPT Algorithms for Photovoltaic Systems

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ABSTRACT

Maximum power point tracking (MPPT) is used to maximize the extraction of the power available from photovoltaic (PV) arrays as irradiance and temperature change. This study compares conventional Perturb and Observe (P&O) and Particle Swarm Optimization (PSO) MPPT algorithms applied independently to the same PV-array/boost-converter system supplying a DC load rated at approximately 10.5 kW. The array comprises 64 monocrystalline PV modules and has an installed nominal capacity of approximately 21.1 kW based on the module rating reported in Table 1. The nominal array capacity, load rating, and instantaneous operating power are distinct quantities; the simulated waveforms show extracted PV power reaching approximately 15–16 kW under the modelled operating conditions. Voltage, current, power, transient response, and steady-state oscillatory behaviour are compared. Both algorithms move the PV operating point toward the maximum-power region. The observed PSO response recovers after the imposed operating transitions, but it also exhibits appreciable current and power oscillations. Accordingly, the results support a balanced comparison between dynamic recovery and steady-state ripple rather than an unconditional claim of superiority for either method.

الأداء المقارن لخوارزمية تتبع نقطة القدرة العظمى المعتمدة على تحسين سرب الجسيمات (PSO-MPPT) وخوارزمية الاضطراب والمراقبة التقليدية (P&O-MPPT) للأنظمة الكهروضوئية

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المخلص	الكلمات المفتاحية
تُستخدم تقنيات تتبع نقطة القدرة العظمى (MPPT) لتعظيم استخراج القدرة المتاحة من مصفوفات الخلايا الكهروضوئية (PV) تحت ظروف تغير الإشعاع الشمسي ودرجة الحرارة. تقدم هذه الدراسة مقارنة بين خوارزمية الاضطراب والمراقبة التقليدية (Perturb and Observe, P&O) وخوارزمية تحسين سرب الجسيمات (Particle Swarm Optimization, PSO) لتتبع نقطة القدرة العظمى، حيث تم تطبيق كل منهما بشكل مستقل على نفس منظومة المصفوفة الكهروضوئية-المحول الرفع للجهد (PV array-boost converter) التي تغذي حملاً تياراً مستمراً بقدرة اسمية تقارب 10.5 كيلوواط. تتكون المصفوفة الكهروضوئية من 64 وحدة كهروضوئية أحادية البلور، بقدرة اسمية كلية مركبة تبلغ حوالي 21.1 كيلوواط. ومن المهم التمييز بين القدرة الاسمية للمصفوفة، وقدرة الحمل، والقدرة التشغيلية اللحظية؛ حيث أظهرت نتائج المحاكاة أن القدرة المستخرجة من النظام الكهروضوئي تصل إلى حوالي 15–16 كيلوواط تحت ظروف التشغيل المدروسة. تم تقييم أداء الخوارزميتين من خلال مقارنة الجهد، والتيار، والقدرة المستخرجة، والاستجابة الانتقالية، والتذبذبات في الحالة المستقرة. أظهرت كلتا الخوارزميتين قدرة على توجيه نقطة تشغيل النظام الكهروضوئي نحو منطقة القدرة العظمى. كما أظهرت خوارزمية PSO قدرة على استعادة نقطة التشغيل بعد حدوث التغيرات المفروضة في ظروف التشغيل، إلا أنها صاحبها تذبذبات ملحوظة في التيار والقدرة. وبناءً عليه، تقدم النتائج مقارنة متوازنة بين أداء التتبع الديناميكي وخصائص التموج في الحالة المستقرة، دون تقديم ادعاء مطلق يتفوق إحدى الخوارزميتين على الأخرى.	المصفوفة الكهروضوئية سرب الجسيمات خوارزمية الاضطراب والمراقبة التقليدية المحول الرفع للجهد الكفاءة

Introduction

Photovoltaic output is nonlinear and depends strongly on solar irradiance, cell temperature, and the connected electrical operating point [1-5]. For every environmental condition, the array has a maximum power point (MPP), whereas maximum power point tracking (MPPT) denotes the control process used to move and maintain the operating point near that

MPP. Effective MPPT is therefore important for extracting the available PV power, particularly when operating conditions vary and the location of the MPP changes [6,7]. Conventional P&O is widely used because of its simple structure and low computational burden, but its fixed perturbation mechanism may cause oscillation around the MPP and can lead to tracking errors during rapid

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environmental changes [8-10]. Population-based approaches such as PSO probe multiple candidate operating points and have therefore been investigated for rapidly changing and partially shaded PV conditions, although their performance remains sensitive to parameter selection, update rate, convergence behavior, and computational burden [11-14]. Recent surveys of next-generation photovoltaics further emphasize material selection, thermal management, and AI-driven optimization as complementary routes to improved PV conversion efficiency and operational robustness [15]. PV material selection and temperature coefficients are also important when evaluating electrical performance and annual energy production in hot-arid environments [1,2].

characteristics of converters, effects caused by environmental conditions or features of Many past works on PV performance, converter characteristics, impact from environment, or characteristics of MPP In many kinds of rated systems for different applications have been analyzed. In that there is no single determination factor to assure equality an MPPT. I.e. In order to be a meaningful and obtain a "fair" comparison all aspects of the comparison need to be the same i.e. PV model, converter design, load specification, environmental profiles, initial conditions as well as initial simulation (initial value for voltage), simulation time (length of time simulated) and many more. Many comparisons available nowadays are based on one waveform without there being any obvious distinction between rated capacity or the actual power the system is being forced to perform at, and some algorithms may attain good fast transient tracking and slow steady-state tracking, and others vice versa. The research herein discussed will observe the P&O and PSO algorithms independently, tracing an array of similar rated PV modules that will be included in a similar boost converter. Voltage, current, and power values, as well as the length of the recovery period and oscillations within each of these values, will be studied.

The aims of the study herein discussed are the ability with which each algorithm will be able to track the MPP to maximize harvested energy from the array and hence make full use of the capacity of the PV array, not that the study is based on improving fundamental PV energy generation capabilities. The specific contribution is a direct, like-for-like comparison of a conventional perturbative method and a population-based method while explicitly distinguishing the MPP from the MPPT control technique and distinguishing installed array capacity, load rating, and observed operating power. This paper is organized as follows. Section two presents the configuration and modelling of the proposed photovoltaic system, including the PV array, DC–DC boost converter, and DC load. Section three describes the operating principles and implementation of the P&O and PSO-based MPPT algorithms, including their control strategies and flowcharts. Finally, Section Four shows the results and the discussion; then, the comparison between P&O-MPPT and PSO-MPPT is shown, considering the variations and responses in voltage tracking, Current response, power extraction, and dynamic and steady-state oscillations. Thus, section five summarizes the most outstanding points and the conclusions.

System Description

The proposed system consists of a PV array, a DC–DC boost converter, an MPPT controller, and a DC load rated at approximately 10.5 kW, as illustrated in Fig. 1. The PV array

converts solar energy into electrical energy, and its current–voltage characteristic changes with irradiance and temperature. P&O and PSO are implemented separately; each algorithm adjusts the converter control variable to move the PV operating point toward the MPP. No online mechanism selects or combines the two algorithms during operation. Comparable PV studies likewise define the array, converter, controller, and load explicitly before evaluating system-level performance [16-19].

The comparison focuses exclusively on P&O and PSO. References to GWO or hybrid Fuzzy GWO–PSO methods are treated only as background and are not part of the implemented comparison. Both algorithms are intended to address changes in the PV operating point, while their performance is assessed in terms of tracking behaviour, recovery, and oscillation.

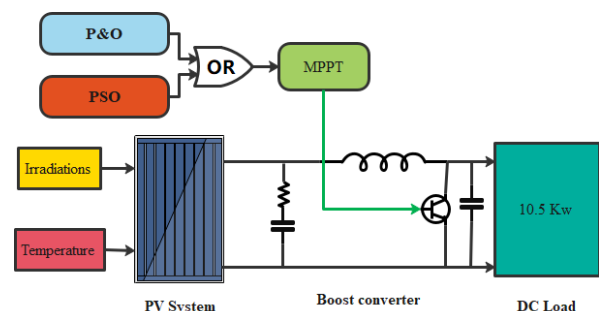


Figure 1: Schematic diagram of the proposed system

PV Modelling

64 monocrystalline SLX 330 PV modules are arrayed in this simulation with eight modules in series per string, and eight strings in parallel. Table 1 lists the module values that are used in the model. For this arrangement of electrical circuits, module, is used. The number of cells in a module, Ncell, is separately indicated.

The PV source is represented by the standard single-diode model. The output current may be expressed as

$$I = I_{ph} - I_0 \left\{ \exp \left[\frac{V + I \cdot R_s}{a \cdot N_s \cdot V_t} \right] - 1 \right\} - \frac{V + I \cdot R_s}{R_{sh}} \quad (1)$$

and the output power is $P = V \cdot I$. Here, I_{ph} is the light-generated current, I_0 is the diode saturation current, R_s and R_{sh} are the series and shunt resistances, a is the diode ideality factor, N_s is the number of series-connected cells, and V_t is the thermal voltage.

An increase in irradiance primarily increases the photocurrent and available power, whereas an increase in cell temperature generally reduces the open-circuit voltage and shifts the MPP. Series connection increases the array voltage, and parallel connection increases the available array current. These relationships determine the I–V and P–V characteristics presented to the MPPT controller. Related work has shown that array configuration, environmental exposure, and simulation-based performance assessment materially influence the interpretation of PV output [20-22].

Table 1: PV module parameters

Max Power (W)	Voc (V)	Vmp (V)	Number of cells	Isc (A)	Imp (A)
329	46	36.9	72	9.48	8.9

Boost Converter

Interfaces between the PV array and the DC load and uses duty cycle control to adjust the operating point of the PV. Consists of an input inductor, a controlled semiconductor switch, an output diode, and an output capacitor. MPPT algorithm does not generate directly an arbitrary switching signal, rather it sets or updates the duty-cycle command and a PWM stage generates the corresponding gate drive signal to the switch. Theoretically, the PV power-to-PV system input voltage relation is:

where D is the duty cycle; it provides the PV to step up the output voltage level and deliver part of the PV output power; it does not generate extra power and does not deliver more than what PV actually generates after the converter's losses. Similar converter-based MPPT structures and duty-cycle control formulations are reported in [9,10,19].

DC Load

The boost-converter output is connected to a DC load with a nominal demand of approximately 10.5 kW. This load rating is different from both the installed nominal capacity of the PV array and the instantaneous power observed in the simulation. The converter performs voltage conversion and power transfer, whereas the MPPT algorithm changes the PV operating point through duty-cycle adjustment to track the MPP. Thus, output-voltage behavior and maximum-power extraction are related but distinct control objectives. The separation between source capacity, converter behavior, and load demand is also important in feasibility and application-oriented PV studies [23-25].

Operating Principle of the Proposed System

The proposed configuration compares a conventional P&O algorithm with a PSO-based MPPT algorithm under the same modelled PV system. Each algorithm is run independently; their outputs are subsequently compared. In each case, irradiance and temperature are applied to the PV array, voltage and current are measured, instantaneous power is calculated, and the algorithm updates the converter duty-cycle command through the PWM stage. The resulting change in converter input impedance shifts the PV operating point toward the MPP. At the broader system level, coordinated PV control and energy-management approaches have also been examined in hybrid and integrated renewable-energy applications [25-28].

- Solar irradiance and temperature are applied to the PV array.
- The PV array produces electrical power according to the instantaneous environmental conditions.
- The PV voltage and current are measured continuously.
- The measured electrical variables are supplied to the MPPT algorithms.
- P&O and PSO determine the appropriate operating point corresponding to the maximum available PV power.
- For each separate simulation run, the active MPPT algorithm updates the converter duty-cycle command.
- The duty ratio of the boost converter is modified accordingly.
- The PV operating point is shifted toward the MPP.
- The boost converter transfers the harvested power to the 10.5-kW DC load.

P&O-MPPT Method

The P&O algorithm measures PV voltage $V(k)$ and current $I(k)$ and calculates instantaneous power as:

$$P(k) = V(k)I(k) \quad (3)$$

It then evaluates:

$$\Delta P = P(k) - P(k-1) \quad (4)$$

And;

$$\Delta V = V(k) - V(k-1) \quad (5)$$

The signs of ΔP and ΔV determine whether the reference voltage is increased or decreased so that the operating point continues toward the MPP; when the perturbation causes power to decrease, the direction is reversed. In the present implementation, the perturbed variable is the reference voltage, with:

$$V_o = \frac{V_{in}}{1-D} \quad (2)$$

$$\Delta V_{ref} = 1V \quad (6)$$

and limits of 0–350 V. The reference is translated by the converter control loop into a duty-cycle command and then into PWM gate pulses. The perturbation step is simulation-specific: a larger step can improve tracking speed but generally increases oscillation around the MPP, whereas a smaller step can reduce ripple at the cost of slower tracking. The procedure is summarized in Fig. 2. The perturbation logic and the associated speed-versus-ripple trade-off are consistent with established P&O implementations and comparative MPPT studies [8-10,13,14].

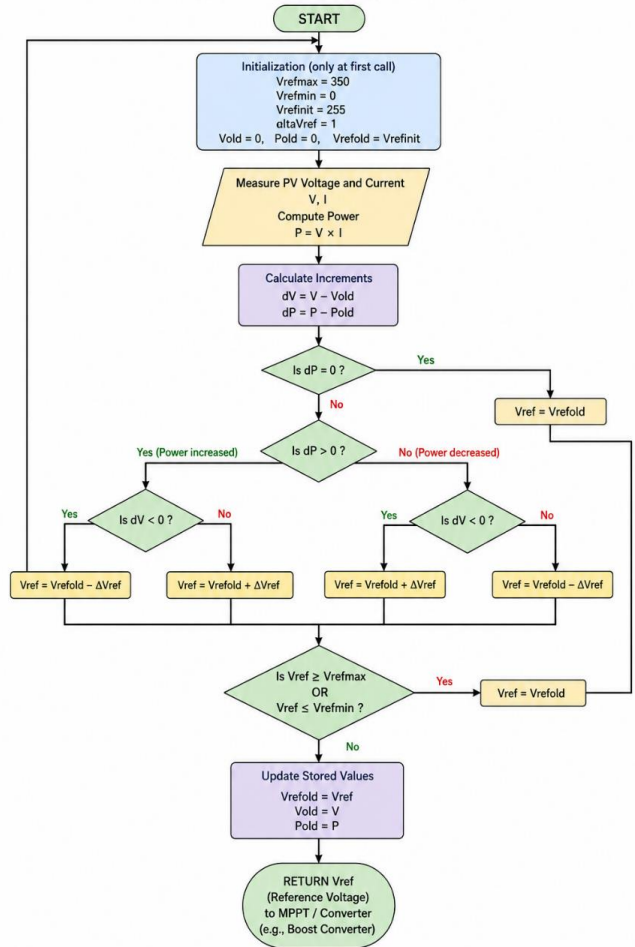


Figure 2: Flowchart of the P&O-MPPT algorithm

PSO-MPPT Method

In the PSO implementation, each particle represents a candidate boost-converter duty cycle D_i . The converter is operated at each candidate value for the prescribed evaluation interval; the corresponding PV power is calculated, and that power is used as the fitness value. Each particle retains its best previously observed position p_{best} , i , while the best

position found by the swarm is stored as g_{best} . Particle velocity and position are updated using:

$$v_i(k+1) = \omega v_i(k) + c_1 r_1 [p_{best,i} - D_i(k)] + c_2 r_2 [g_{best} - D_i(k)] \quad (7)$$

$$D_i(k+1) = D_i(k) + v_i(k+1) \quad (8)$$

subject to the permitted duty-cycle limits. The updated duty cycle is passed to the PWM stage, and the process is repeated until the implemented stopping condition is satisfied. The present model uses eight particles. Figure 3 summarizes this sequence. This particle-based search mechanism follows the general PSO-MPPT framework used in recent comparative and hybrid optimization studies [11-13].

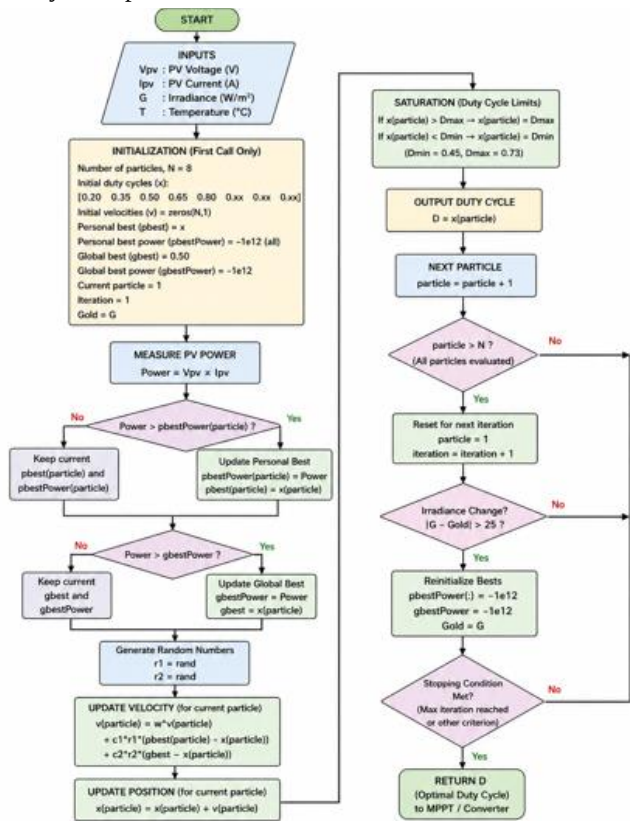


Figure 3: Flowchart of the PSO-MPPT algorithm

Results and Discussion

Figure 4 presents the measured PV current IBO, PV voltage VBO, and PV power PBO for the system operated with the P&O-MPPT algorithm. The three waveforms are interpreted together to assess the movement of the PV operating point and the oscillatory behavior of the controller.

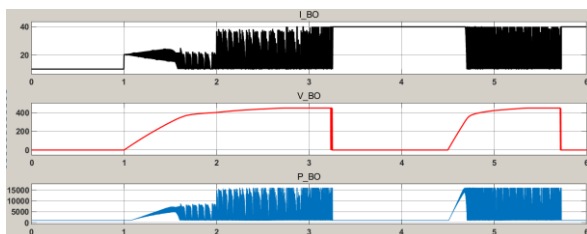


Figure 4: P&O-MPPT output waveforms

The simulated MPPT response of the photovoltaic system in certain time. The upper, middle, and lower plots represent the PV current, voltage, and power, respectively. Initially, the PV voltage and power are near zero, but the PV current is around 10 A, and the MPPT controller starts tracking the maximum available power. As such PV voltage varies from nearly 0V

to 380-400 V, whereas PV power vary from 1KW to 7-8KW, showing that the MPPT controller can track the maximum power region. Whereas current varies from nearly 10A to 25 A, and power is between a few kilowatts

The PV current rises and exhibits substantial high-frequency oscillations, reaching approximately 35-40 A, while the PV voltage increases toward approximately 400-450 V. As a result, the PV power increases to approximately 15-16 kW. Although the current waveform contains considerable ripple,

A second tracking event occurs at approximately 4.5 s. The PV voltage rapidly increases from zero and reaches approximately 350-400 V, followed by a rapid increase in PV power. Within approximately 0.2-0.3 s, the power reaches approximately 15-16 kW. From approximately 4.8 to 5.7 s, the PV power remains close to 15.5-16 kW, while the voltage is maintained around 400-450 V. The relatively stable power level confirms that the MPPT controller successfully maintains operation near the maximum-power point. However, the high-frequency oscillations visible particularly in the current waveform indicate that the converter/controller dynamics could be further optimized to reduce current ripple and improve steady-state performance. Table 1 illustrates the P&O-MPPT output. Table 2 illustrates P&O-MPPT output the observed trade-off between tracking recovery and steady-state ripple is consistent with the behavior discussed in comparative P&O studies [8,13,14].

Table 2: P&O-MPPT output

Parameter	Approximate observed value
PV current	10-40 A
Maximum PV voltage	400-450 V
Maximum PV power	15-16 kW
Initial tracking time	≈ 1 s
Second tracking event	≈ 4.5 s
Approximate power settling after second event	0.2-0.3 s
Steady-state power	≈ 15.5-16 kW

The P&O controller increases PV voltage and power from their initial values toward the observed maximum-power region. Following the second operating transition, the waveforms return to the higher-power region. The values in Table 2 are approximate readings from the plotted response and should therefore be interpreted as waveform-based observations rather than independently calculated performance indices.

Figure 5 presents IBO, VBO, and PBO for the same PV system operated independently with the PSO-MPPT algorithm. GWO is not implemented in this simulation. The waveforms show the transient and oscillatory behavior of PSO under the modelled operating sequence.

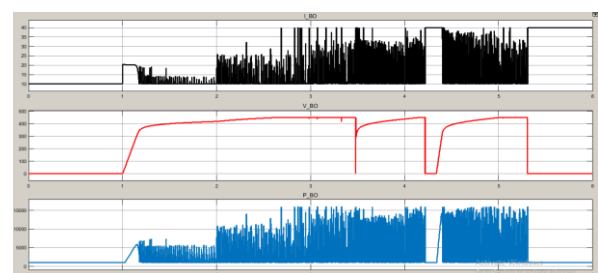


Figure 5: PSO-MPPT output waveforms

The output current I_{BO} shows significant variations throughout the simulation: From 0–1 s, the current is approximately 10 A, indicating the initial operating condition. Around 1 s, the current increases and then exhibits strong oscillations between approximately 10 and 20 A. From 2–3.5 s, the current increases considerably, with peaks approaching 40 A. Between approximately 3.5 and 4.2 s, the current remains highly variable but generally stays at a relatively high level. A similar high-current operating region occurs from 4.4 to 5.3 s. After approximately 5.3 s, the current falls to zero, indicating that the PV/converter output is no longer delivering power. The large fluctuations in current are characteristic of a system operating under rapidly changing PV operating conditions and/or MPPT duty-cycle perturbations. However, the current remains bounded and follows the changes in the available PV power.

The voltage response is considerably smoother than the current response. Initially, the voltage is approximately zero. At about 1 s, it rapidly rises to approximately 350 V, after which it gradually increases toward approximately 400–450 V. The voltage reaches approximately 400–420 V during 1.5–2.5 s, 440–450 V around 3–3.4 s, approximately 330–450 V after the first interruption, and approximately 350–450 V during the final operating interval. Two major voltage interruptions are visible around 3.5 s and 4.2 s, where the voltage temporarily falls to zero before recovering. These events are also reflected in the power waveform.

The output power follows the combined behavior of voltage and current. During the initial period, the power is approximately 1 kW. After the voltage rises, the power increases to approximately 5–7 kW. From approximately 2–3 s, the available output power increases substantially, reaching approximately 10–16 kW, although with considerable oscillation. The maximum instantaneous power in the figure is approximately 16 kW. The power then decreases during the transient interruptions around 3.5 s and 4.2 s, before recovering to approximately 12–16 kW. Similar PSO-based studies report that dynamic recovery can be accompanied by oscillatory behavior when the search and converter dynamics are not fully damped [11–14].

Comparison between P&O MPPT and PSO MPPT

P&O and PSO are compared using the same output variables: PV current, PV voltage, and PV power. Table 3 summarizes the waveform-based observations. Because the present figures do not provide independently calculated tracking-efficiency or ripple indices, the comparison is stated cautiously and distinguishes transient recovery from steady-state oscillation. For interpretation of such waveform variations, recent PV condition-monitoring work also emphasizes examining electrical signatures together rather than relying on a single variable [30–32].

The reported waveforms indicate that both algorithms move the PV system into a higher-power operating region. The PSO case recovers after the voltage and power interruptions visible near 3.5 s and 4.2 s, but it also exhibits appreciable current and power oscillations. These interruptions are shown in the PSO response and should not be attributed to P&O. On the evidence currently reported, PSO may be described as showing recovery after the observed transitions, while P&O and PSO both retain steady-state oscillatory behavior. Consequently, the comparison demonstrates a trade-off between transient recovery and ripple; it does not establish unconditional superiority without additional quantitative performance indices. This cautious interpretation is consistent

with comparative MPPT literature, where algorithmic performance depends on the test conditions and on the chosen transient and steady-state metrics [6,13,14,30].

Table 3: Qualitative comparison of P&O-MPPT and PSO-MPPT based on the reported waveforms

Parameter	P&O MPPT result	PSO MPPT result
Voltage tracking	Reaches the operating region shown in Fig. 4	Reaches the operating region and recovers after the interruptions shown in Fig. 5
Current response	Variable response with visible ripple	Pronounced high-frequency oscillations
Power response	Power is extracted with visible oscillation	Power reaches the reported region with stronger fluctuations
Dynamic response	Tracks the operating transitions shown in Fig. 4	Recovers after the voltage and power interruptions shown in Fig. 5
Steady-state ripple	Visible in the reported waveforms	Relatively high, particularly in current and power
Overall MPPT performance	Successful tracking with waveform oscillation	Successful recovery with a trade-off in current and power ripple

Conclusion

In this study, it has been examined on the basis on the simulated values with respective P&O-MPPT and PSO-MPPT independently implementing on the same PV-array/boost-converter configuration. The differences between the installed capacity of the PV array, the load rating, and the instantaneous harvested power have been clear. The experiments depicted show that both the algorithms drive PV operating point towards the detected maximum-power.

While the PSO's output is recovered after the break occurring, which appears on the voltage and power graphs of PSO; large ripple currents and power exist on the PSO's operation and therefore it seems that the selection between dynamic recovery and ripple depends on its respective weight and it cannot be clearly proved that PSO always shows optimal solution.

Based on just these conditions a ranking cannot be made on MPPT algorithm or its control capability, as optimization of components values and switching pattern is missing in this study. A relevant comparison should be made based on uniform test conditions and calculated numerical evaluation on average power yield, MPPT efficiency, setting time etc.

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