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Application of Modern Optimization Techniques for Maximum Power Point Tracking of Solar Photovoltaic Systems Under Constant Temperature and Partial Shading Conditions

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Abstract: *The electricity sector has been undergoing profound transformations. In particular, the Portuguese self-consumer regime has allowed customers of the medium and low voltage electricity grid to be producers/consumers of electricity, actively contributing to greater energy efficiency. In this context, the energy that comes from the sun is not used to its maximum. In addition, photovoltaic cells have a characteristic operating curve (voltage vs. current), in which any operating point is reflected. Within this curve, there is a particular point known as the maximum power point (MPP) at which the cell supplies the maximum power output to a load. If the cell does not operate at this point, it has lower efficiency values. To harness maximum power under standard and dynamic shading conditions, there are various techniques of low complexity for capturing maximum power. We present a maximum power point tracking (MPPT) algorithm capable of dealing with the problem of partial shading. This algorithm involves modifying one of the most used algorithms within photovoltaic systems, known as P&O, using a simulated annealing (SA) algorithm. P&O is often used due to its straightforward implementation, but it is susceptible to partial shade conditions. Sampling was added to this algorithm to a better approach to the point of maximum power using the SA, and then to attain a more precise convergence with P&O. Implementing a maximum power point tracking method under partial shading was the major goal of this study.*

Keywords: Global Maximum Power Point (GMPP); Local Maximum Power Point (LMPP); Simulated Annealing (SA); Perturbation and Observation (P&O)

I. INTRODUCTION

Traditional energy sources, such as fossil fuels and nuclear energy, have environmental, social and political problems because they are highly polluting. Due to the constant energy demand of the industrial sector and the increase in the use of electrical equipment in a variety of human activities, the demand for electrical energy has increased exponentially in recent decades. Renewable energy sources are sustainable alternatives to meet the need for electricity, provide the diversification of the matrix and increase energy security for countries in terms of supply. Options for generating renewable energy include hydraulic, biomass, wind, and solar [1]. Among renewable sources, solar energy has great potential to contribute to the world's demand for electricity, especially in countries with high levels of solar radiation. The world's solar energy power in 2015 was 227 GW, and the prospect is to reach a power of 1362 GW by 2030. This source encompasses large solar plants or parks, and distributed generation on the roofs of buildings [2]. Photovoltaic cells have characteristic V-I curves that define their behavior under
different operating conditions. The power of a solar cell is given by the product of the current and the voltage of the cell. The maximum power point (MPP) is the product of the voltage at the maximum point (VMPP) and current at the maximum point (IMPP) for which the power extracted from the photovoltaic system is maximum (PMPP). The maximum power point varies continuously, depending on factors such as the temperature of the solar cell and the irradiance

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conditions. To increase the competitiveness of PV energy with respect to other types, it is necessary to increase its efficiency, which is low, or reduce the costs. The MPP changes over time since it depends on the temperature and the level of irradiance; therefore, to make the photovoltaic modules operate close to the MPP point, the use of tracking algorithms is needed to be linked to a power converter, which is usually a direct current to direct current (DC/DC) device. The photovoltaic module then delivers specific current and voltage values that maximize power delivery.

To deal with nonlinear phenomena and achieve system stability with MPPT, many approaches have been proposed in the literature, such as techniques with adapted constant voltage [3], fuzzy logic [4–6], neural Networks [7,8], perturbation and observation (P&O) [9–12], and incremental conductance [13–15].

The choice of technique depends on factors such as speed and accuracy in tracking, the level of complexity of the sensors used, and the cost of the necessary equipment. Conventional techniques, such as perturbation and observation, and incremental conductance, have easy implementation. Techniques based on artificial intelligence, such as particle swarm optimization, and ant colony optimization, as well as techniques based on fuzzy logic and artificial neural networks, have a greater degree of complexity and require greater computational effort [16].

Regarding efficiency, two situations must be analyzed. When the system is subjected to homogeneous levels of irradiance, when all its modules receive the same value of solar power, conventional techniques are able to track the MPPT efficiently. However, when the modules receive different levels of irradiance in a condition known as partial shading or PSC (partial shading condition), the PV curve, due to the construction of the modules, has more than one power peak, one of which is a global peak and the others, with lower power values, are known as local peaks [17].

In this condition, conventional techniques track the first peak found, which can be a global or a local one, resulting in a loss of power if tracking a local peak. Therefore, under PSC, it is preferable to use techniques capable of distinguishing the power level between the different peaks. In this case, the best examples are based on artificial intelligent concepts. Several algorithms are used to track the maximum power point, as already mentioned when they come across the LMPP points, and PSO (Particle Swarm Optimization), ACO (Ant Colony Optimizer), and Gray Wolf Optimization (GWO) algorithm are used to solve the problems associated with partial shading [18–20].

In our research, new hybrid techniques were implemented experimentally and theoretically. The proposed optimization system, based on a meta-heuristic SA, conducts the operation of the boost converter to GMPP promptly and accurately under any of the shading conditions. To perform the MPPT, the SA algorithm is used separately. Its combination with the P&O, initiating the SA-P&O algorithms, boosts converter operation to GMPP under any of the conditions. To evaluate the performance of the SA and SA-P&O-based MPPT algorithms, a comparison was made with the traditional MPPT algorithm, i.e., the P&O method. The implemented MPPT techniques were compared and evaluated considering convergence time, the amplitude of the steady-state oscillations in the MPP, and the methods' efficiencies during uniform irradiance and partial shading.

II. LITERATURE REVIEW

A detailed literature survey has been carried out in the area of solar PV System & incremental conductance MPPT algorithm.

Saravana Selvan (2013) have detailed the incremental conductance MPPT algorithm and verifying experimentally through the modelling of PV system with MPPT algorithm in MATLAB. MPPT is the methodology that detects the maximum power point from array input ranging the ratio between voltage and current delivered to extract as much power as possible.

Kaouane*et al.* (2016) have addressed the implementation of an MPPT algorithm into a capacitor storage-based DC-DC converter for PV systems is presented in this work. The Incremental Conductance MPPT algorithm is used in the suggested photovoltaic system to study a ZETA converter controlled by the Pulse Width Modulation (PWM) technique which allows transferring the maximum amount of power from the generator to the load in which choosing a suitable duty cycle step size and computing the time of response are critical. In MATLAB/Simulink, the proposed photovoltaic system is simulated.

Saad Motahhir (2018) have presented the modified Incremental conductance algorithm technique to detect the maximum power even at increased sun irradiance. The effects of altering solar irradiance, temperature, series and shunt resistances and partial shade on the output of the PV panel are described using this model.

Shang *et al.* (2020) have suggested an Enhanced Incremental Conductance algorithm of control to improve the efficiency and economy of PV system. This approach differs from the typical incremental conductance algorithm in that it can distinguish the instantaneous increment of current, voltage, and power when the external environment changes, which can improve tracking efficiency. Under rapidly changing solar radiation levels, MATLAB simulations are done and outcomes of enhanced and standard incremental conductance algorithm are compared.

Teo *et al.* (2018) have presented an investigation of the effects of partial shading and the key region that lowers shading heaviness susceptibility. It uses a photovoltaic string made of modules connected in series. The study of the P-V characteristic curve under various numbers of shaded modules and shading heaviness implies that when the irradiance of the shaded modules reaches a specific critical point, the photovoltaic string becomes insusceptible to shading heaviness. Depending on how many shaded modules there are, the critical point may change.

Libin Xu *et al.* (2020) MPPT technique have proposed to increase response time. It is made up of a computing stage and a controlling stage. The broad positioning operation and the fine positioning operation are both included in the computing stage. Additionally, a starting duty cycle value is generated during the calculation stage based on the IV curves and the DC-DC converter's properties. The computing stage can increase response time while the tracking efficiency is improved by the regulating stage's short step-size regulation of the DC-DC converter's duty cycle.

Abdelsalam*et al.* (2011) have described a P&O MPPT approach that has been modified for use with PV systems. Due to the nonlinearity in the characteristics of PV modules, high-efficiency PV based micro-grids require maximum power point tracking (MPPT) controllers to maximise the captured energy. Perturb and observe (P&O) approaches still have a number of drawbacks, including user-defined constants, quick tracking versus oscillation trade-offs, and sustained oscillation about the MPP.

Jose Pombo *et al.* (2018) have presented a technique for maximum power point tracking (MPPT) using the particle swarm optimization (PSO) algorithm with adjustable step size to avoid steady state oscillations. This will ensure that the effect of partial shade on a photovoltaic (PV) system's effectiveness will be avoided.

III. PROPOSED METHODOLOGY

The simulated annealing method in Figure 1 is based on a metallurgy technique, and involves controlled heating and cooling of a material. This technique aims to reduce defects by increasing the size of a material’s crystals.

The heating and cooling of the material affect the temperature and the free thermodynamic energy. Although the same decrease in temperature causes the same decrease in free thermodynamic energy, cooling at a given rate causes a more significant reduction in free energy. This temperature reduction approach is implemented in the simulated annealing algorithm as it is the optimum solution [24–26].

The method starts with a random solution, Pi and selects a neighboring solution Pk. After calculating the cost of the two solutions, their difference DP = Pk - Pi is calculated. If DP is less than zero, then the value of the objective function of the neighboring solution is better, and replaces the current solution Pi with Pk. If DP is greater than or equal to zero, the solution with the worst result is accepted.

The value of this probability decreases with the number of iterations. If the value of pr is more significant than a random number between zero and one, the solution with the worst result is accepted. This procedure is repeated until a stopping criterion is satisfied. One of the main advantages of this algorithm is that it allows testing solutions that differ from those currently available. It thus minimizes the possibility of the energy generated by the system oscillating over a local maximum point indefinitely.

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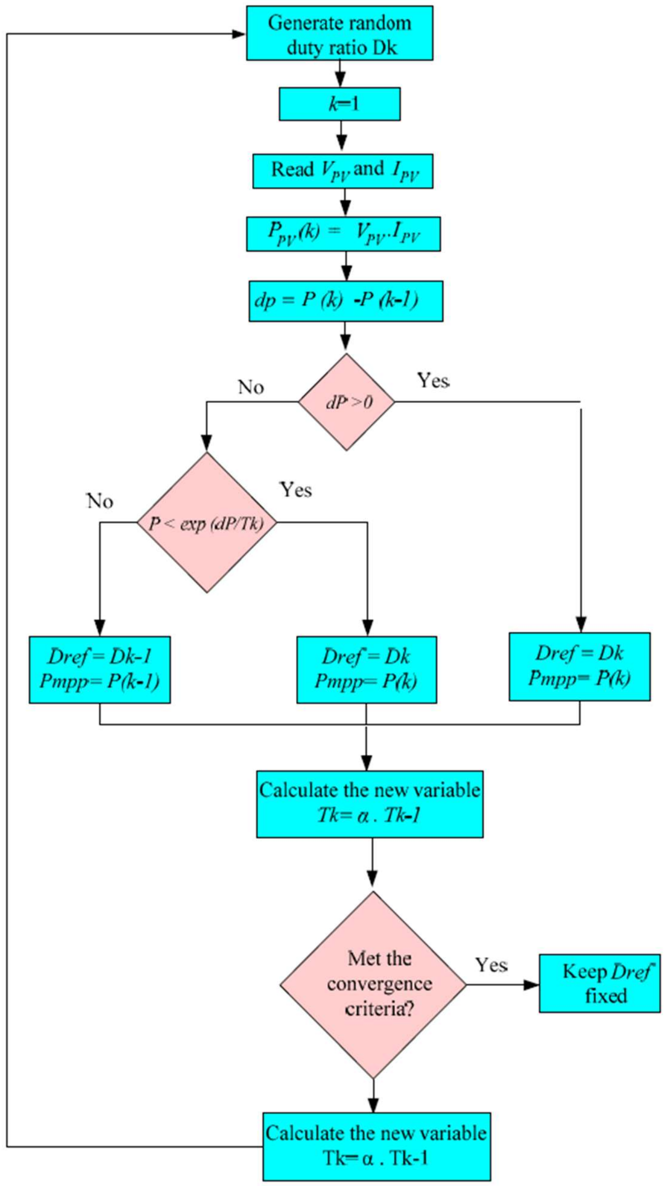

Fig 1 Flowchart of the SA technique.

3.1. Perturbation and Observation (P&O) Algorithm

The P&O method is based on the modification of the trip ratio or duty cycle (D) of the boost converter that modifies the value of the current supplied by the photovoltaic panel. This method consists of monitoring the board operating voltage (Vpv); for example, if the voltage rises (disturbance) and the power drawn by the load increases (observation) it means that the operating point has moved towards the maximum power point, at which point the operating voltage should be disturbed in the same direction. By contrast, if the power extracted by the load decreases, the operating point has moved in the opposite direction to the maximum power point as evidenced in the flow diagram in Figure 2.

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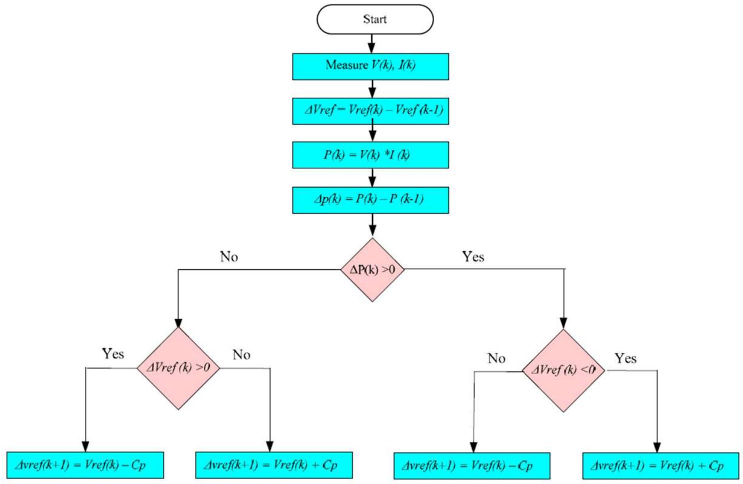

Figure 2. Flowchart of the P&O technique.

3.2. SA-P&O Algorithm

The SA-P&O algorithm uses the SA technique to reach a point close to the global maximum power point. Soon after finding it, the algorithm switches to the P&O method, which starts with referencing the best power point found defined by the SA method. Figure 13 shows the flowchart for this algorithm, the SA-P&O MPPT. Figure 3 shows the SA-P&O hybrid MPPT algorithm.

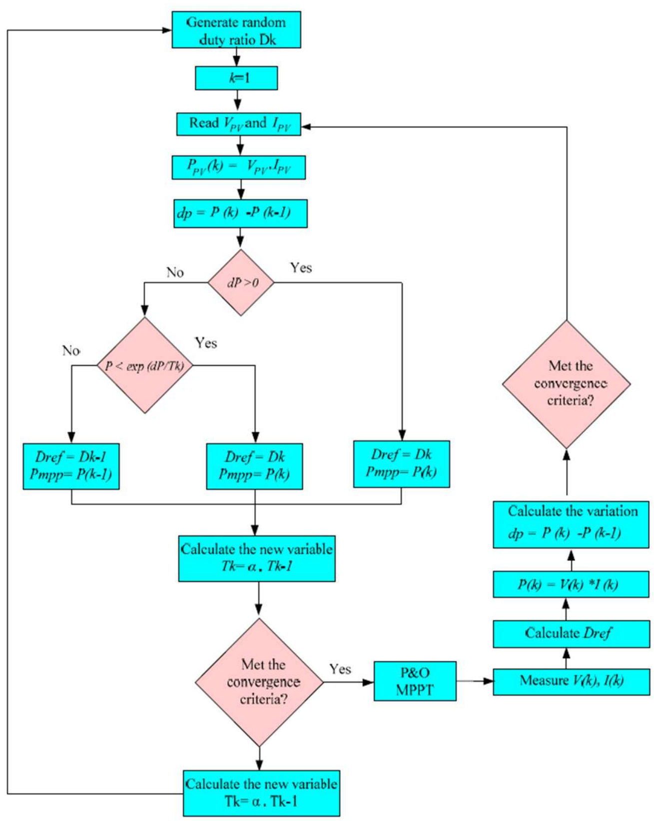

Figure 3. Flowchart of the SA-P&O technique.

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IV. PROPOSED SIMULINK

The Simulink diagram represents a Maximum Power Point Tracking (MPPT) system for a solar photovoltaic (PV) array under constant temperature and partial shading conditions. The primary objective of the system is to extract the maximum available power from the PV array despite variations in solar irradiance caused by partial shading.

The system begins with the PV array, which receives two inputs: constant temperature, typically maintained at 25°C, and a variable irradiance pattern representing partial shading conditions. The PV array generates voltage and current, denoted by and . These parameters are continuously measured and supplied to the MPPT controller. The controller calculates the PV power using and determines the appropriate duty cycle for the DC–DC converter.

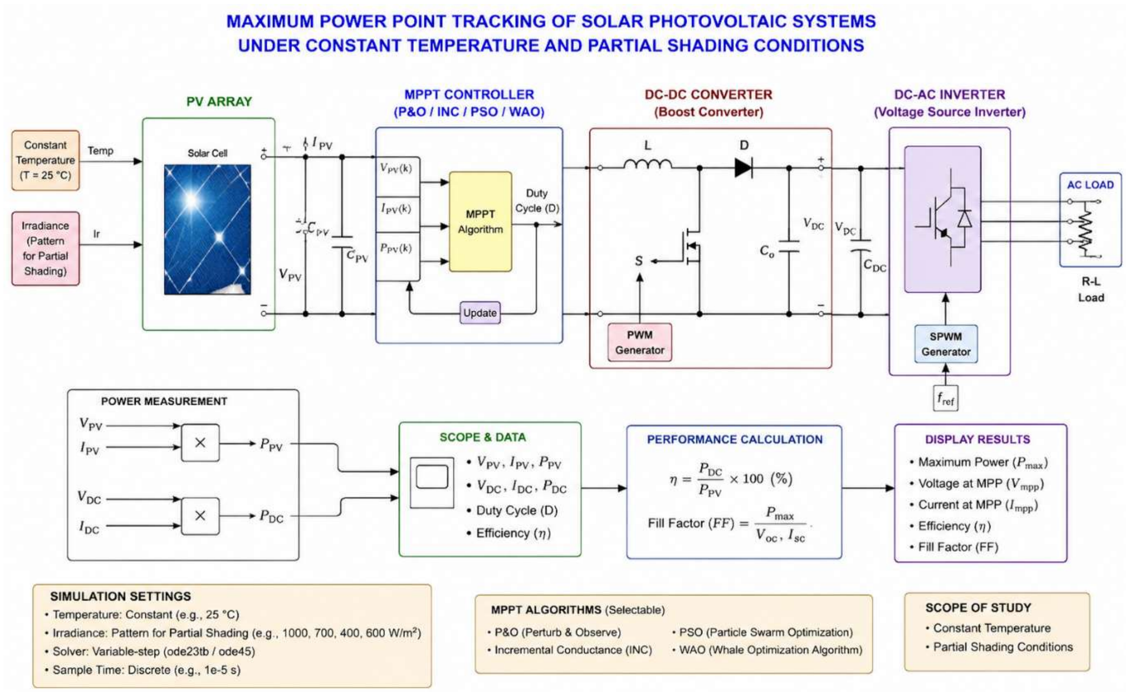

Fig 4 Proposed Simulink Model

The MPPT algorithm can employ techniques such as Perturb and Observe (P&O), Incremental Conductance (INC), Particle Swarm Optimization (PSO), or Whale Optimization Algorithm (WAO). The generated duty cycle controls the switching operation of the boost DC–DC converter, which increases and regulates the DC-link voltage.

The regulated DC power is then supplied to the DC–AC voltage-source inverter. An SPWM generator produces the switching pulses required to operate the inverter, which supplies power to the R-L load.

The lower section performs power measurement and performance evaluation by calculating , , efficiency, maximum power, MPP voltage, MPP current, and fill factor. Scope blocks display the electrical parameters and MPPT response, enabling comparison of different algorithms under partial shading conditions.

V. RESULT ANALYSIS & DISCUSION

The performance of the SA-P&O-based MPPT algorithm was evaluated using experimental results for the system configuration shown in Figure 4. An empirical analysis was performed using Micro lab box for the implementation of the MPPT, a DC-DC boost converter, a DC/AC converter to adapt the voltage to the connection grid utility, and a passive L filter were used. The SA-P&O-based MPPT algorithm was compared to the traditional P & O-based MPPT algorithm. Both MPPT algorithms were compared considering the following cases: (1) the photovoltaic arrangement operates in STC, and case (2) when the photovoltaic arrangement works under partial shading conditions. In the latter case, two photovoltaic panels were partially shaded, in which the first was subjected to 300 W/m² solar radiation, while the second

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was subjected to 500 W/m² solar radiation. The MPPT algorithms were evaluated under two different operating conditions of the PV system. Figure 4a shows the first testing condition characteristic curves (case 1) of the PV module, Figure 4b shows the characteristic curves for case 2, and Figure 5c shows case 3. A transparent sheet covered parts of the PV array to simulate partial shading with different patterns in cases 1, 2, and 3.

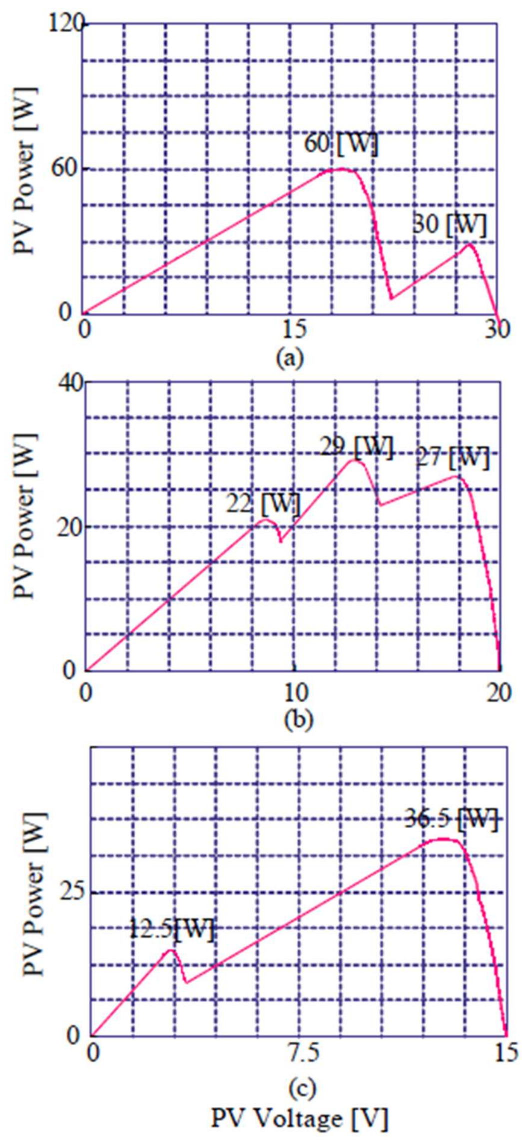

Figure 5. PV characteristics: (**a**) case 1, (**b**) case 2, (**c**) case 3.

The experimental results presented in this section show the power extracted from the PV array and the voltage and current at the array's output terminals obtained for each MPPT algorithm. Figure 5 illustrates the power extracted from the PV array operating under partial shading conditions using the P&O algorithm. As shown in Figure 4, the characteristic curve Ppv × Vpv has one GMPP and two LMPP, with the GMPP equal to 60 W and the LMPP equal to 30 W. The P&O method reached the GMPP first and maintained this value.

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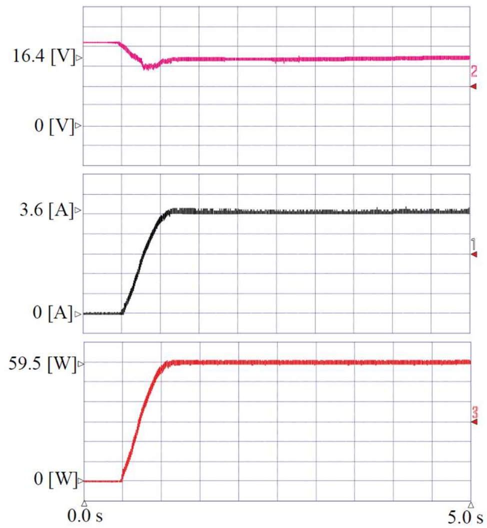

Figure 5. Experimental results of P&O MPPT for case 1.

Figure 6 shows the power extracted from the PV array for the SA-based MPPT algorithm. GMPP was achieved, and the method produced a power of 60 W. In addition, this MPPT method resulted in reduced power fluctuations in steady-state. The results demonstrate that the SA-P&O-based MPPT algorithm can quickly convert to GMPP when the PV array operates under partial shading conditions. In addition, the proposed MPPT method consistently showed less power fluctuation and greater efficiency in tracking when compared to the traditional method (P&O).

Figures 5 and 6 show that the P&O method takes longer to achieve the MPPT and suffers from steady-state ripples more than the SA-P&O. Figure 7 shows the PV voltage, current, and power when the SA-P&O method was used under partial shading conditions when the maximum local and global forces, respectively, were 22 W and 29 W. GMPP was achieved with low power oscillation and short convergence time. Experimental results involving power, voltage, and current of the PV array of the P&O method are shown in Figure 19. The results indicates that the MPPT algorithm based on the P&O way did not reach the GMPP, becoming fixed at an LMPP of 22 W. Moreover, the MPPT algorithm showed more significant power fluctuations and had the longest convergence time.

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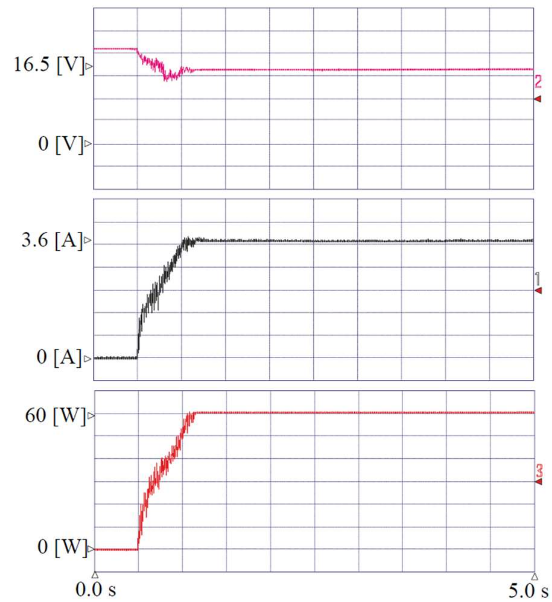

Figure 6 Experimental results of SA-P&O MPPT considering case 1.

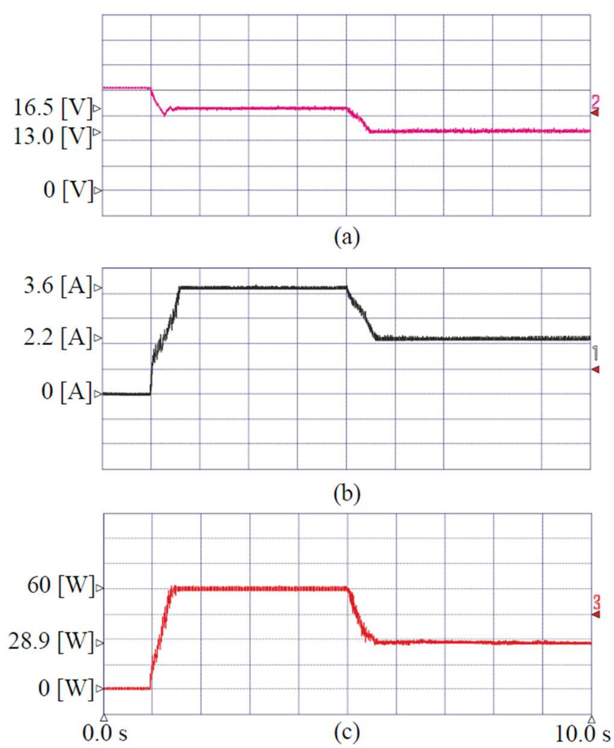

Figure 7. Experimental results of SA-P&O MPPT considering Case 2 (**a**) PV voltage, (**b**) PV current, and (**c**) PV power.

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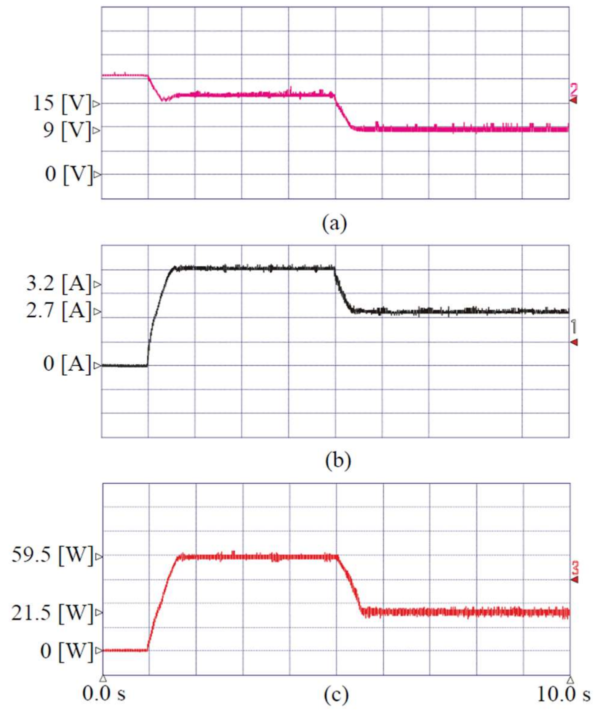

Figure 8. Experimental results of P&O MPPT considering Case 2. (**a**) PV voltage, (**b**) PV current, and (**c**) PV power

In case 3, the PV array was exposed to nominal irradiance, and then a part of the PV was covered by the transparent sheet. The method tracked the global MPP at 36.5 W without fixing on a local MPP, as shown in Figure 9. However, the P&O process fixed on local MPP tracking at 12.5 W and failed to find the global MPP, as shown in Figure 10. By comparing the performance of P&O and SA-P&O methods, it was found that the tracking time was reduced by 18.5% when the latter method was used, and the most important advantage was avoiding the LMPP.

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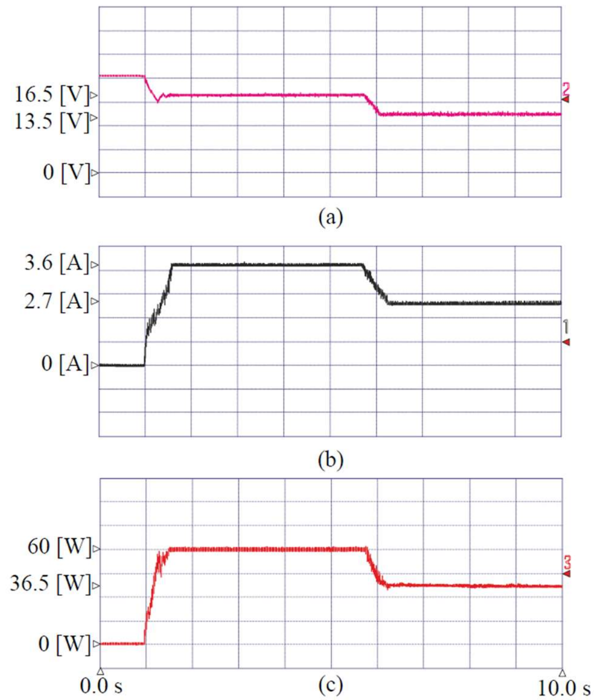

Figure 9. Experimental results of SA-P&O MPPT considering Case 3. (**a**) PV voltage, (**b**) PV current, and (**c**) PV power.

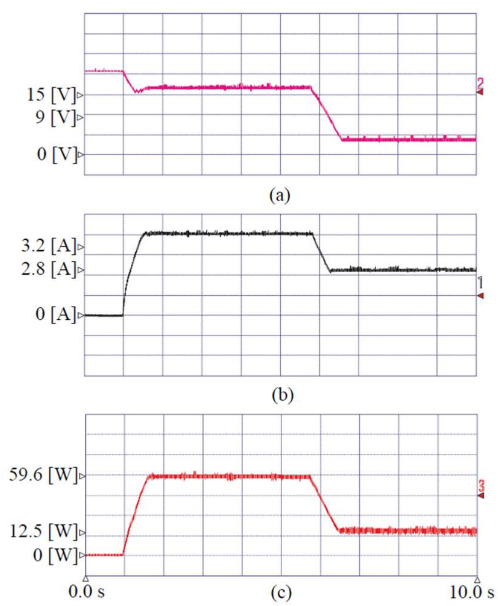

Figure 10. Experimental results of P&O MPPT considering Case 3. (**a**) PV voltage, (**b**) PV current, and (**c**) PV power.

VI. COMPARATIVE ANALYSIS

Case 1: Single GMPP (≈60 W) with two local maxima (≈30 W)

Table 1. Experimental Comparison for Case 1

Parameter	P&O	SA-P&O
Operating Condition	Partial Shading	Partial Shading
GMPP	60 W	60 W
LMPP	30 W	30 W (avoided)
GMPP Achieved	Yes	Yes
Tracking Time	Longer	Faster
Steady-State Oscillation	High	Low
Power Ripple	Larger	Smaller
Stability	Moderate	High
Overall Performance	Good	Excellent

Case 2: Multiple Peaks (LMPP = 22 W, GMPP = 29 W)

Table 2. Experimental Comparison for Case 2

Parameter	P&O	SA-P&O
Operating Condition	Partial Shading	Partial Shading
Global MPP	29 W	29 W
Local MPP	22 W	22 W
Final Operating Point	Fixed at 22 W (LMPP)	Reached 29 W (GMPP)
GMPP Tracking	No	Yes
LMPP Avoidance	No	Yes
Convergence Time	Longest	Short
Power Oscillation	High	Low
Tracking Accuracy	Poor	Excellent
Overall Performance	Poor	Excellent

Case 3: Dynamic Partial Shading

Table 3. Experimental Comparison for Case 3

Parameter	P&O	SA-P&O
Initial Condition	Uniform Irradiance	Uniform Irradiance
Shading Applied	Yes	Yes
Global MPP	36.5 W	36.5 W
Local MPP	12.5 W	12.5 W
Final Operating Point	Fixed at 12.5 W	Reached 36.5 W
GMPP Tracking	No	Yes
LMPP Avoidance	No	Yes
Dynamic Response	Slow	Fast
Stability	Moderate	High
Overall Performance	Poor	Excellent

Table 3. Quantitative Performance Comparison

Performance Metric	P&O	SA-P&O	Improvement
GMPP Tracking Capability	Partial	Complete	Improved
LMPP Avoidance	No	Yes	Significant
Tracking Speed	Moderate	Fast	18.5% Faster

Convergence Time	High	Low	Reduced by 18.5%
Steady-State Ripple	High	Low	Reduced
Power Oscillation	High	Low	Reduced
Tracking Accuracy	Moderate	High	Improved
Performance under Partial Shading	Moderate	Excellent	Significant

VII. CONCLUSION

We present the results of implementing an SA-P&O-based MPPT algorithm for extracting the maximum power from photovoltaic arrays. The efficiency of the MPPT algorithm was validated by comparison with the MPPT P&O algorithm. From the results obtained using computational simulation, it was demonstrated that the SA-P&O-based MPPT algorithm was able to quickly converge to GMPP when the photovoltaic arrangement was operating in STC, and when it is subjected to partial shading conditions. In addition, use of the SA-P&O-based MPPT algorithm resulted in reduced power oscillations in steady-state and greater tracking efficiency in the search of the GMPP.

Therefore, the SA-P&O-based MPPT method has an excellent performance in dealing with local and global maximums in PV systems subjected to partial shading, maximizing the system's overall efficiency. Since our approach simulated conditions of real irradiation, our results indicate excellent applicability of the technique to any PV system for delivering maximum power output regardless of irradiation conditions and shading. As demonstrated quantitatively, the proposed optimization method allows attainment of the best possible power, which can guarantee maximum energy production from an entire PV system, with the shortest financial return time for the investor. Our results show that the SA-P&O method followed the GMPP efficiently in all STC and PSC operating conditions and reduced transient periods, which increased the generated energy and reduced the convergence time under all operating conditions. In addition to the accurate converge to GMPP, SA-P&O requires fewer parameters than other metaheuristics methods. The disadvantages of the proposed method are oscillations around the MPP, and the complex computations required.

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