A Hybrid MPPT Algorithm based on DE-IC for Photovoltaic Systems under Partial Shading Conditions

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Abstract. This paper presents a hybrid maximum power point tracking (MPPT), which combines a metaheuristic algorithm and a traditional MPPT method applied in a photovoltaic system operating under partial shading conditions. The MPPTs based on traditional methods are not able to track the global maximum power point (GMPP) when partial shadings occur. Thus, MPPT algorithms based on metaheuristic algorithms, which are used for global optimization, have presented efficiency to extract the maximum power from photovoltaic arrays. However, these methods are random, resulting in large power oscillations in transients of small variations in solar irradiance. Therefore, this paper proposes the metaheuristic algorithm called Differential Evolution (DE) to seek and track the GMPP. After the DE convergence, the MPPT algorithm is switched to Incremental Conductance (IC) in order to refine the tracking. The effectiveness of the algorithm is proved through simulation results. Furthermore, comparative analyses are provided for each algorithm (DE and IC) to evaluate their performances in the PV system.

Keywords: Photovoltaic System, Maximum Power Point Tracking, Differential Evolution, Incremental Conductance.

1 Introduction

In the past years, power generators based on new renewable energy resources, such as wind, solar, and fuel cells, have been considered prominent solutions to complement the demand for energy supply and overcome environmental issues [1]. In particular, the solar energy resource, using photovoltaic (PV) generators, has been distinguished due to its availability, noise-free, easy installation, and low maintenance [2]. Therefore, PV systems are seen to be suitable for adoption in the distributed generation modality as well as in autonomous applications.

Several research studies have discussed the assessment of efficiency and performance for PV systems developing proper technologies and materials according to the application [3-5]. On the other hand, PV systems deal with non-linear electrical characteristics, which are influenced by weather conditions such as solar irradiance and temperature, which means that the power produced by PV modules, is weather-dependent [2]. Nevertheless, since the output power-voltage (P-V) characteristic curve of a PV array has a maximum power point (MPP), appropriate maximum power point tracking (MPPT) techniques can be employed to maximize the overall system efficiency [2].

Under uniform solar irradiance, the MPP can accurately be tracked by using traditional MPPTs, such as Perturb and Observe (P&O), Incremental Conductance (IC), constant-voltage tracing, and Beta [3]. However, when partial shading conditions occur, the PV array can be exposed to different levels of solar irradiance, which can limit its power generation. [5]. To mitigate this effect, bypass diodes can be used across the PV modules to protect them and provide alternatives path for the currents. Consequently, with this strategy, the P-V curve exhibits multiple local MPP (LMPP) and only one global MPP (GMPP), making the tracking more challenging for the traditional methods, which may not be able to differentiate the LMPPs from the GMPP, resulting in power losses [4-6].

To overcome the problems associated with partial shading conditions, as well as with the LMPPs and GMPPs, a large number of MPPT algorithms based on meta-heuristic methods, have been proposed in the literature, such as particle swarm optimization [5], ant colony optimizer, bat search algorithm, grey wolf optimization (GWO), whale optimization, genetic algorithms, among others [5,7]. Some research reviews on these MPPT techniques have been undertaken to compare their performances related to convergence-time, computational efforts, and power oscillations [6-9].

In general, despite the effectiveness on seek the GMPP, the inherent drawback of the meta-heuristics MPPTs consists of randomness. Once they need to perform the whole search space on the P-V curve, even minimal changes in solar irradiance imply large power oscillations. To overcome this drawback, hybrid methods, that combine two or more algorithms, have great potential that can be explored in more detail [8].

In this context, among the several existing meta-heuristic algorithms, the differential-evolution (DE), based on genetic algorithm, has been highlighted [10-12]. The DE algorithm can be used for global optimization to obtain the solution for practical problems which have noncontinuous and nonlinear characteristics or have many local minima or constraints [11]. Moreover, DE requires few for fine-tuning. The research work depicted in [10], relies upon DE to perform the MPPT in a partial shading PV system, however, large power oscillations were obtained and the effect caused by minimal changes in solar irradiance was not evaluated.

In this paper, a combined algorithm is proposed incorporating the DE and IC methods, resulting in a hybrid MPPT technique. Firstly, the DE method performs the GMPP tracking, when achieving the convergence, the IC method acts to avoid large power oscillations in steady-state. Therefore, tracking efficiency, convergence time, and accuracy can be improved with the hybrid algorithm (DE-IC), in comparison with their versions implemented only as DE or as IC. To evaluate the performance, the MPPT algorithm is applied to a PV system composed of a PV array, a dc-dc boost converter, and a resistive load. Moreover, comparative analysis considering the MPPTs based on IC, DE, and DE-IC is provided by means of computational analysis.

2 PV system description

The electrical power circuit of the PV system implemented in this paper is presented in Fig. 1. The system consists of a PV array composed of four series-connected PV modules, resulting in a power generation around to 980 W at standard test conditions (STC). A dc-dc boost converter is employed to interface the PV array and the load.

In the referred PV system, the MPPT algorithm is carried out by the control system of the dc-dc boost converter. The dc-dc boost converter is controlled by using two control loops, as presented in Fig. 1. A voltage loop is adopted to control the PV array voltage (v_{pv}), whose voltage reference is provided by the MPPT algorithm, while an inner current control loop is employed to control the boost inductor current (i_{Lb}), whose reference is obtained from the voltage loop.

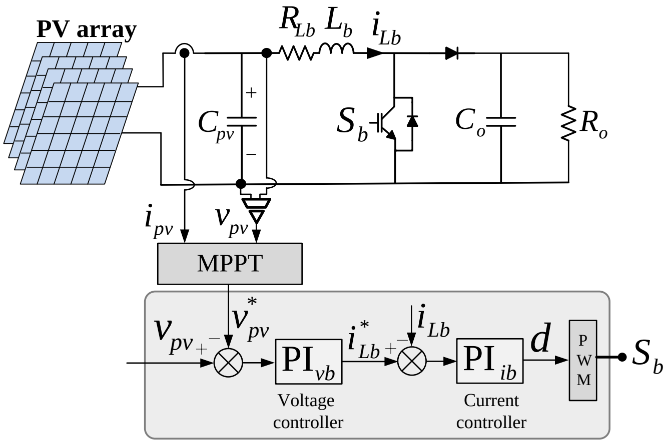


Fig. 1. The electrical power circuit and control system of the PV system.

3 MPPT techniques

The IC method is based on detecting the slope of the characteristic P-V curve. The power slope of the PV array is null at MPP (dP/dV = 0), as well as positive on the left, and negative on the right of the curve [3]. Thus, due to this condition, this algorithm can track the MPP by using the increment in the array conductance. Therefore, the algorithm tends to change the reference values, in this case, the voltage reference (v_{pv}^*), according to a pre-defined fixed increment step always seeking to remain in the maximum point. The flowchart of the IC implemented as MPPT is represented in Fig. 2.

On the other hand, the DE is a metaheuristic algorithm classified as an evolutionary method, which was proposed by Storn and Price for global optimization [12]. The DE works on creating a target vector to represent a population of individuals. In order to achieve the problem solution, a few interactions are needed to submit the created population to the following genetic operators: mutation, crossover, and selection [10,12]. Thus, for each interaction, the evolved individuals are evaluated as a possible solution until an attained satisfactory criterion or a termination condition.

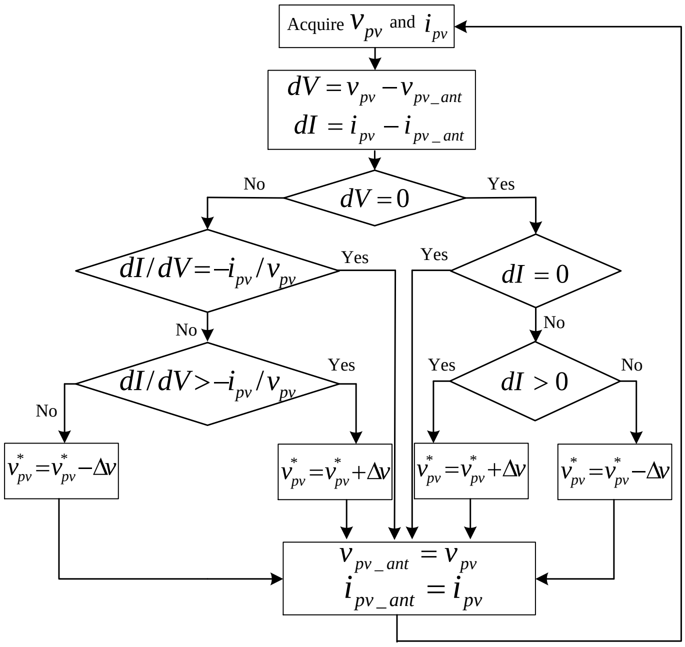


Fig. 2. IC-based MPPT method.

Thus, the initial population of the target vectors $x_{i,G}$, can be generated as follows:

$$x_{i,G},\ i = 1,2,3 \dots NP \tag{1}$$

where NP is the total number of individuals and the index G is the vector's generation.

After that, three target vectors are randomly selected to the mutation process, which works by using a mutation factor to provide a weighted difference between two target vectors. Then, the weighted difference is added to the third target vector to obtain the mutant vector $v_{i,G+1}$, as given by:

$$v_{i,G+1} = x_{1,G} + F(x_{2,G} - x_{3,G}) \tag{2}$$

where $x_{1,G}, x_{2,G}$ and $x_{3,G}$ are the selected target vectors and F is the mutation factor usually chosen in the range of [0,2]. This process can be associated with the advantage through competition between the individuals, where each individual in a community is learning from the difference between each other and generates the better individual in order to ensure the promotion of the community.

In sequence, the crossover operation is introduced in the DE in order to promote diversity among mutant vectors. Therefore, the mutant vectors $v_{i,G+1}$ when combined with target vectors $(x_{i,G})$, can generates trial vectors $u_{i,G+1}$, according to the condition:

$$u_{i,G+1} = \begin{cases} v_{1,G+1}, & \text{if } rand_i \le C_r \\ x_{1,G+1}, & rand_i > C_r \end{cases} \tag{3}$$

where a random number $rand_i$ in the range of [0, 1] is compared with the crossover rate C_r, which is a control variable in the range of [0,1].

After the results of the crossover process, the trial vector is evaluated in a fitness function, which is associated with the problem statement. If the trial vector performs the best solution when compared with the target vector, then the trial vector is used as the target vector for the next generation. This operation is the selection and can be described as:

$$x_{i,G+1} = \begin{cases} u_{1,G+1}, & f_{fitness}\left(u_{1,G+1}\right) < f_{fitness}\left(x_{1,G}\right) \\ x_{1,G}, & otherwise \end{cases} \tag{4}$$

In this paper, as previously mentioned, the MPPT algorithm provides the reference voltage to the control system of the dc-dc boost converter. Thus, considering the DE to the MPPT application, the target vectors are equivalent to the PV array reference voltages, and the solutions resulting from each iteration are equivalent to the PV array output power. Therefore, the initialization of the target vector in (1) can be rewritten in the proposed DE-MPPT algorithm as follows:

$$v_{pvi}^{*}, \ i = 1,2,3 \dots NP \tag{5}$$

where $v_{pvi,G}^{*}$ represents the PV array reference voltages as target vectors.

The global best solution is obtained by comparing all the solutions for the NP reference voltages. In this case, the PV array power is considered as the solution, in which the highest power is selected as the best solution, and its corresponding v_{pvi}^{*} is considered as the best individual $v_{pv\_best}^{*}$ of such population. The flowchart of the DE-MPPT is presented in Fig. 3.

In certain cases, the performances of the meta-heuristic algorithms can be affected under small variations of solar irradiance, resulting in large power oscillations. To overcome this problem, this work proposes to combine both techniques (DE and IC) to take advantage of each one through a hybrid algorithm. The proposed hybrid technique can improve the performance in GMPP tracking under conditions that resemble practical applications. Firstly, the DE method performs the GMPP tracking, when achieving the convergence, the IC method acts to avoid large power oscillations in steady-state. Fig. 4 presents the flowchart of the hybrid algorithm DE-IC developed in this paper.

4 Simulation Results

The effectiveness of the presented MPPT techniques was evaluated by means of simulation results using MATLAB/Simulink computational tool. Table 1 presents the electrical characteristics of the PV modules, while Table 2 summarizes the main parameters of the PV system related to the dc-dc boost converter and load, as well as the DE and IC MPPT parameters.

The MPPT techniques were tested considering different operational scenarios as depicted in Fig. 5. In Case 1, represented in Fig.5a, the PV array is exposed to uniform solar irradiances at $1000 \ \mathrm{W/m^2}$. As can be observed, the P-V curve presents only one MPP at 981 W.

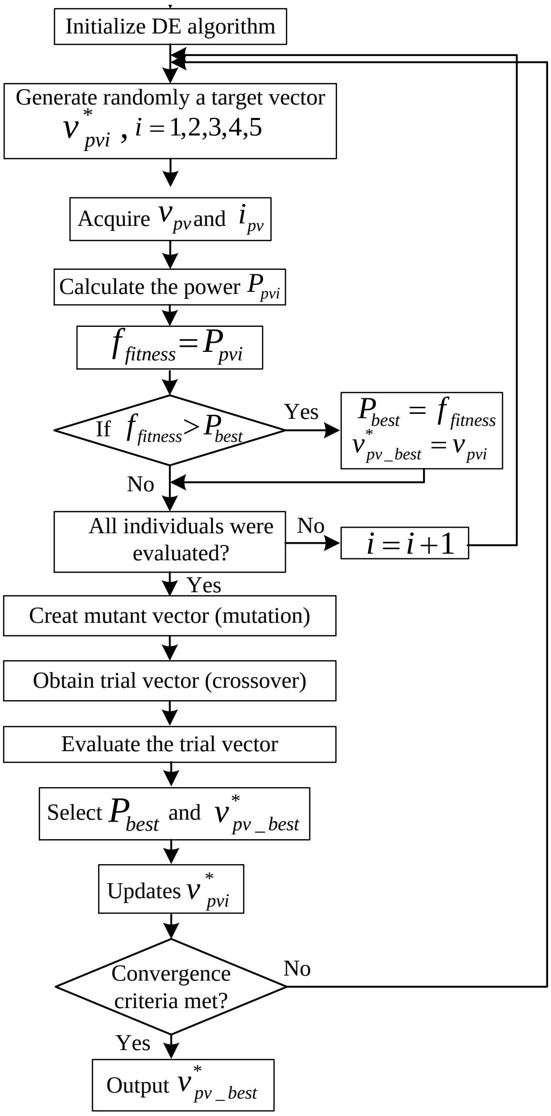


Fig. 3. DE-based MPPT method.

On the other hand, in Case 2, the PV array was subjected to partial shading conditions, as illustrated in Fig. 5b. In this case, the two upper PV modules of the string are subjected to three steps of solar irradiance, resulting in three different patterns of partial shading. In pattern 1 of partial shading (PS1), from the beginning to 3s of the simulation time, the two upper PV modules are exposed to $900\ \mathrm{W/m^2}$ of solar irradiance. In sequence, in pattern 2 (PS2), from 3 to 5s, $800\ \mathrm{W/m^2}$, and then $1000\ \mathrm{W/m^2}$ for pattern 3 (PS3). The other two modules of the PV array remain unchanged, operating at $300\ \mathrm{W/m^2}$. Moreover, as can be seen from the P-V curves presented in Fig.5b, the highest power is found in the PS3 with the GMPP located at 478 W. Under PS1 and

PS2 conditions, the maximum power is 427 W and 379 W respectively. As expected, the LMPP remains at 310 W for the three patterns of partial shading since solar irradiance has not been changed for the two bottom PV modules.

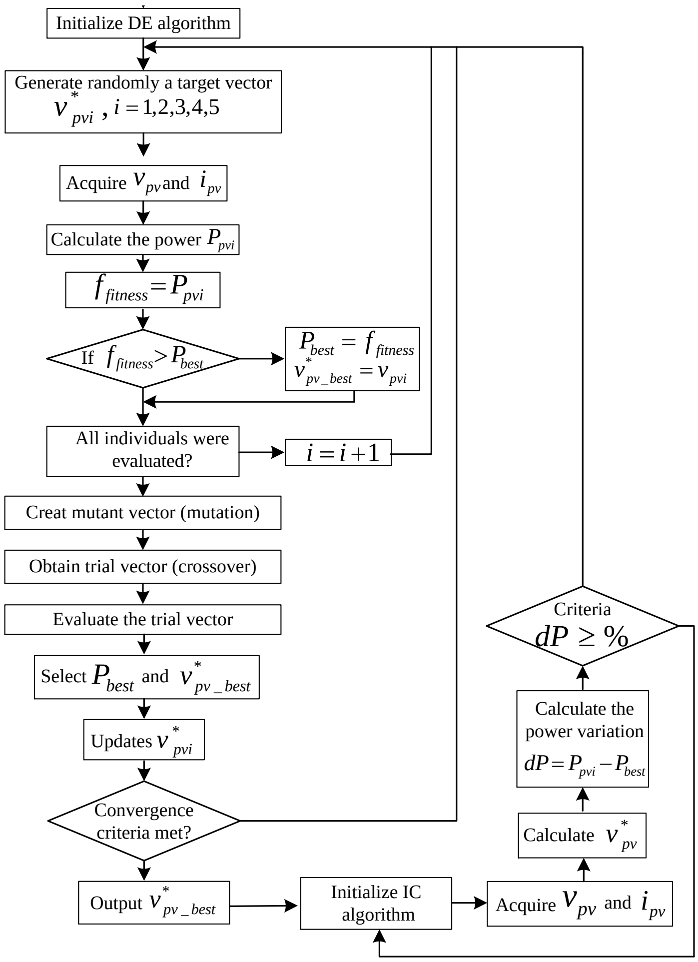


Fig. 4. DE-IC-based MPPT method.

Table 1. Parameters of the photovoltaic (PV) Module at STC.

Parameter	Value
Maximum PV power	245 W
MPP Voltage	30.8 V
MPP Current	7.96 A
Open circuit voltage	37.7 V
Short circuit current	8.25 A

Table 2. Simulation parameters.

Parameter	Value
Boost inductive filter (L_b)	1.5 mH
Capacitive filter (C_{pv})	235 uF
Output capacitance (C_o)	470 uF
Load resistance (R_o)	61.9 Ω
Switching frequency	20 kHz
PI voltage controller gains	$KP_v = 0.1170$ $KI_v = 16.7618$
PI current controller gains	$KP_i = 0.0634$ $KI_i = 302.064$

Parameter	Value
DE control variables	
Population size (NP)	5
Mutation Factor (F)	0.5
Crossover rate (C_r)	0.99
Maximum number of generation (G)	60
Power variation	15 %
IC variable	
Increment (Δv)	1 V

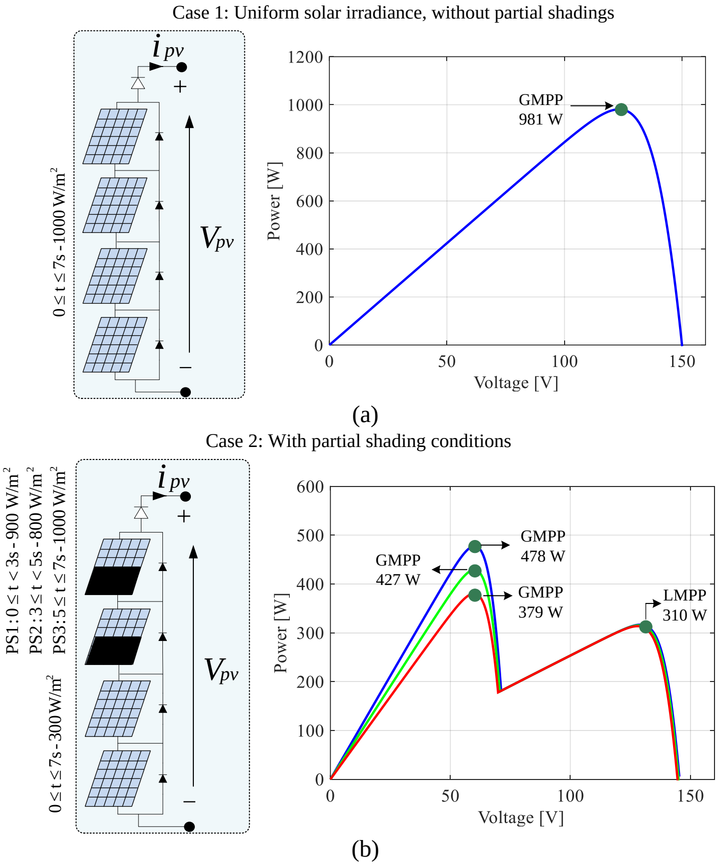


Fig. 5. PV array characteristic curves (P-V): (a) PV array under uniform solar irradiance; (b) PV array under partial shading conditions.

4.1 Case 1: PV system operating under uniform solar irradiance

Fig. 6 shows the simulation results, taking into account the power extracted from the PV array (P_{pv}) by the MPPT techniques, the PV array voltage (v_{pv}), and the PV array current (i_{pv}), under uniform solar irradiance conditions. From Fig.6, it can be noted that all the implemented MPPT techniques were able to achieve a point close to the GMPP, around 981 W. As can be seen, in the transitory state, the DE-based MPPT and DE-IC-based MPPT algorithms presented high power oscillations due to randomness searching. However, under the steady state, the DE algorithm showed small power oscillations compared to IC and DE-IC. Table 3 summarizes the results obtained for Case 1. In terms of convergence time, the IC reached better results when compared with the others, since the MPPTs based on DE took more time in searching space to track the GMPP. On the other hand, the tracking efficiency, calculated from the ratio of the total extracted PV power by the available one, of the hybrid DE-IC resulted in a better performance when compared with the traditional IC and with the DE-based MPPT.

Table 3. Comparison performances among the MPPT techniques based on IC, DE and DE-IC.

Parameter	IC		DE		DE-IC	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
PV power extracted [W]	975.5	307	975.7	463	980	476
Tracking efficiency [%]	99.44	99.03	99.46	96.86	99.89	99.58
Convergence time [s]	0.6	1.8	1.2	2.3	1.4	1.8

4.2 Case 2: PV system operating under partial shading conditions

Fig. 7 corresponds to the simulation results of Case 2. In this case, three different patterns of partial shading conditions are considered. As can be seen from the results presented in Fig.7a, the conventional technique based on IC was not able to track the GMPP during the three conditions, demonstrating that its performance was affected when partial shading occurs. On the other hand, as shown in Fig. 7b and Fig. 7c, the MPPT algorithm based on DE as well as the hybrid DE-IC algorithm can sweep the PV characteristic curve exploring all its domains to seek and track the GMPP for different situations.

Considering the partial shading conditions, both MPPTs DE and DE-IC tracked a point close to the GMPP. However, in the hybrid algorithm, the IC method continues the tracking after DE convergence in order to refine the search closer to the ideal operating point of the PV array. As a result, the MPPT based on DE-IC extracted more power from the PV array, making it more efficient when compared with the MPPT-DE.

Small variations of solar irradiance tend to represent real situations for operational conditions of a PV system. Nevertheless, the MPPTs based on metaheuristic algorithms require a margin of power variation to restart the random searching and operate properly in transitory conditions. In this work, the power variation was considered 15% of the PV array power. Therefore, small steps of solar irradiance could not be enough to restart the tracking. Hence, it is possible to notice that the algorithm MPPT-DE-IC was able to adapt to the small steps of solar irradiation while maintaining high efficiency in all partial shading patterns. In addition, the MPPT-DE-IC presents lower power oscillations in both transitory and steady states in comparison with the MPPT-DE. Table 3 presents the performance results obtained for PS3 of Case 2, for all implemented MPPT algorithms.

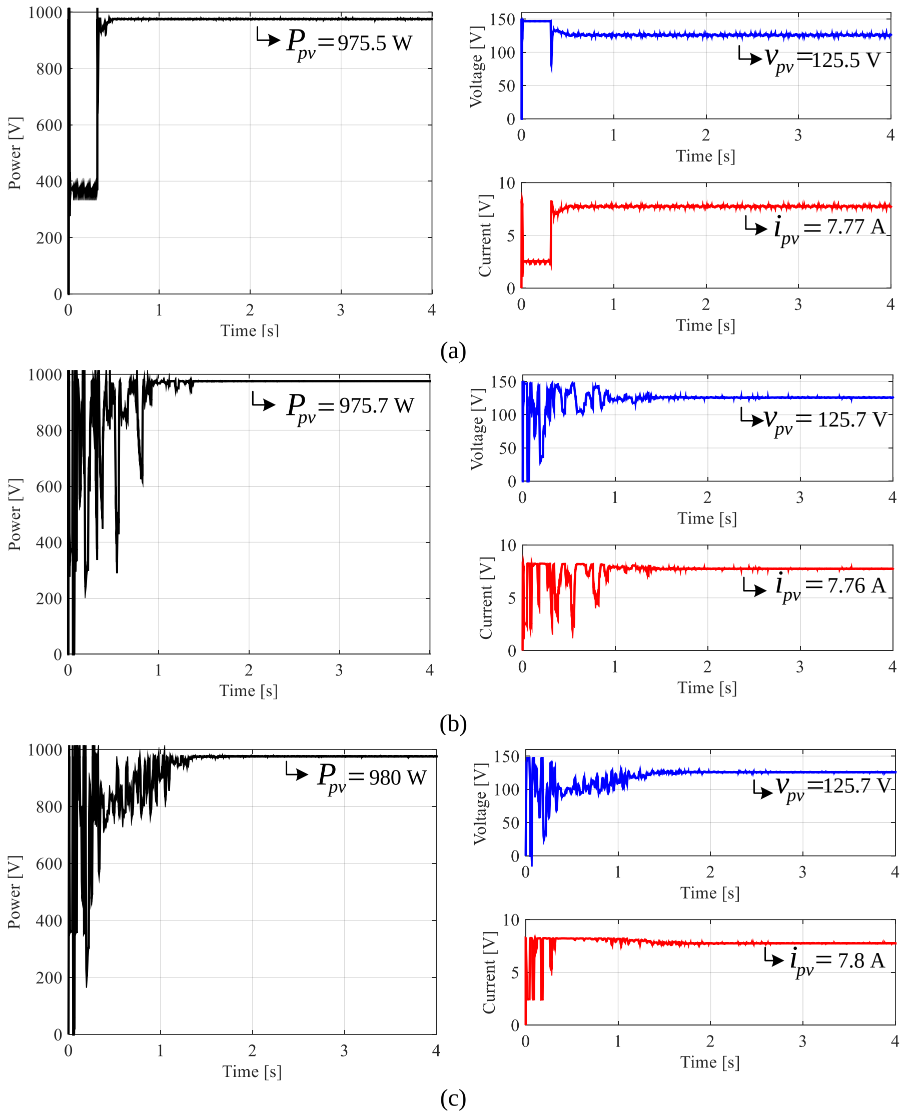
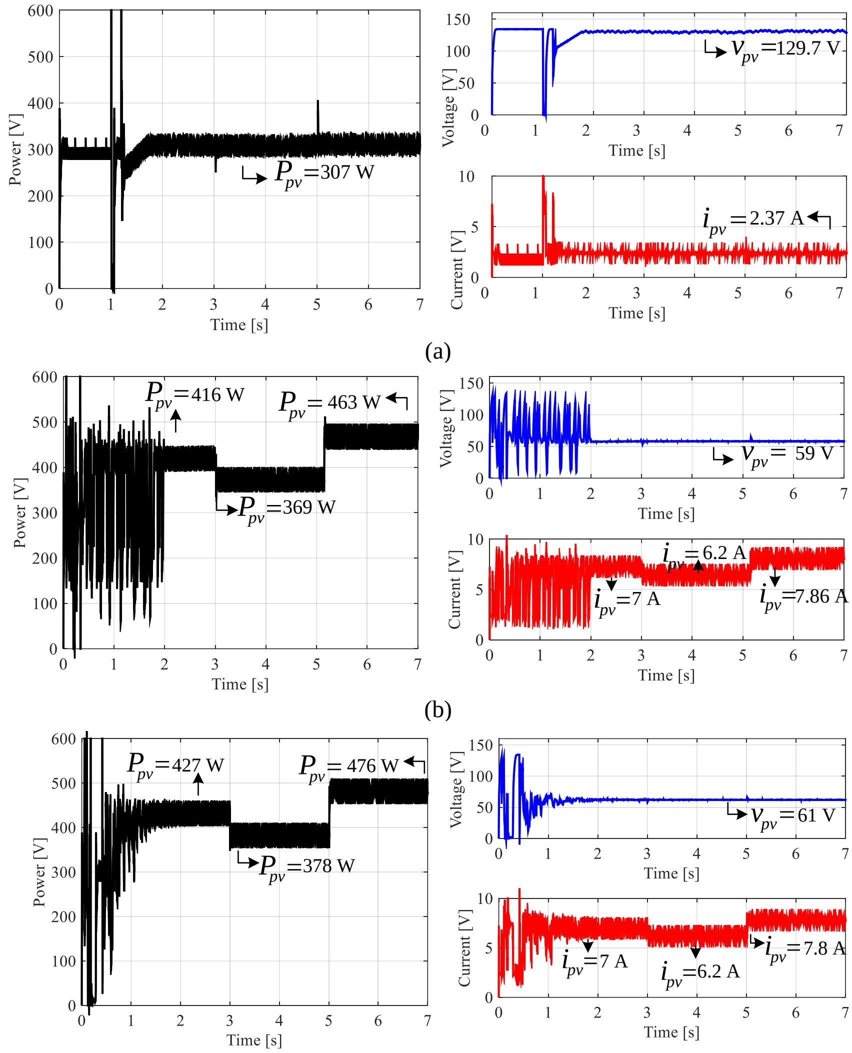


Fig. 6. Simulation results for the MPPT algorithms considering the PV system operating under uniform solar irradiance: (a) IC-based MPPT; (b) DE-based; (c) DE-IC-based MPPT.

5 Conclusions

This study presented a hybrid algorithm based on DE and IC methods to carry out the MPPT technique in a PV generation system. Such methods were implemented individually, resulting in the MPPT-IC and MPPT-DE algorithms, as well as through a hybrid method proposed by MPPT-DE-IC. The effectiveness of the algorithms was verified through simulation results for different operational conditions. Under uniform solar irradiance (Case 1), the MPPT algorithms based on IC, DE, and DE-IC presented satisfactory performances searching a point close to the GMPP. The efficiency of the hybrid method was superior, due to the ability of the IC adjustments after the DE convergence. On the other hand, when the PV array was subjected to partial shadings (Case 2), the MPPT-IC demonstrated the limitation of conventional methods, tracking only the LMPP and keeping stable at this point. Meanwhile, methods based on meta-heuristic optimization MPPT-DE and MPPT-DE-IC were able to track the GMPP.



(a)

(b)

(c)

Fig. 7. Simulation results for the MPPT algorithms considering the PV system operating under partial shading conditions: (a) IC-based MPPT; (b) DE-based; (c) DE-IC-based MPPT.

Finally, the proposed MPPT-DE-IC presented the overall best performance when compared to the other algorithms. In addition, the hybrid algorithm is able to maintain the GMPP tracked even in small changes in solar irradiance, which is not possible through techniques based only on meta-heuristic optimization. So the losses are minimized as well as the performance of the algorithm makes it superior.

Acknowledgments

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