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A Comparative Study of Different MPPT Methods for Grid-Connected Partially Shaded Photovoltaic Systems

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Abstract-Partial shading is considered as one of the unavoidable complicated phenomenon in solar power generation systems. Under shade, the photovoltaic characteristics display numerous local maxima.Such situations are very challenging for Maximum Power Point Tracking conventional techniques for reaching the global maximum, which considerably reduces the PV systems' energy yield. This paper suggests a comparative analysis between the several MPPT algorithms for partially shaded grid-connected photovoltaic system. Indeed, these techniques involve the fuzzy logic as well as the genetic algorithm methods. The grid side control is also investigated in this work through the development of different control loops. Simulation tests have been performed under MATLAB/Simulink environment to highlight the suggested method's effectiveness.

KeywordsPartial shading, photovoltaic system, maximum power point tracking (MPPT), Fuzzy logic Control (FLC), Genetic Algorithm (GA).

1. Introduction

Interested to the concerns of energy availability and environmental safety, the photovoltaic (PV) systems installation has been considerably increased [1]. The PV application has been expanded from providing small electronics to large power stations coupled to the grid. Considerable work has therefore been interested to improving the system performance, especially on the development of maximum power point tracking (MPPT) methods. The Perturb and Observe (P&O), suggested in [2], is practically the mainly used owing to its simple implementation. However, next to unpredicted sunlight changes it can miss the maximum power point (MPP). The Incremental Conductance technique (Inc-Cond), proposed in [3], overcomes some P&O drawbacks. However, it requires more complex computing capacity and memory. More recently, several soft computing based algorithms have been applied for PV applications mainly due to their emblematic reasoning, explanatory ability, and flexibility [4]. These techniques are valuable to handle nonlinear and complex systems. However, they cannot deal with the partially shaded conditions (PSC). Under shade, the situation is complicated as the PV array displays several local maxima (LMs) [5].The existence of numerous peaks decreases the present MPPT efficiency due to their inability to differentiate the global maximum (GM) among the LMs. In [6] studies have indicated that the power losses resulting from the classical MPPT methods convergence difficulty may be up to 70%. Thus, the improvement of the MPPT process is required.

In this framework, several researchers have studied the MPP tracking challenge. In [7], the direct search technique is developed. Authors in [8] have studied an MPPT algorithm using operating point information acquired on individualsolar panels.

Authors in [9] highlight the robustness of an MPPTapproach based on the genetic algorithm (GA) for various operational conditions under PSC.

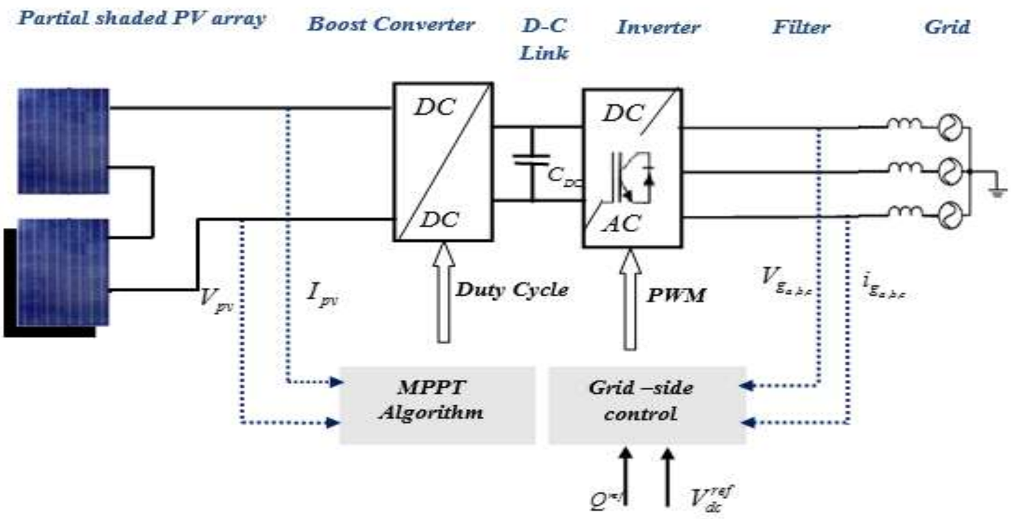


Fig.1. Block diagram of the studied system

This paper suggests the design of an optimal MPPT for shaded PV system linked to the main utility grid. The GA based MPPT is used to follow efficiently the GM under all operating states. The developed technique is studied and compared with a Fuzzy Logic Controller based technique (FLC). The transfer of energy to the grid is assured through several control loops.

In our study, we started by the description of the partially shaded grid -connected photovoltaic system. In fact, in this section the PV system comportment under PSC is studied and the different MPPT algorithms are presented. then the electrical network side control is developed. Third the mismatch power loss concept is presented. The performance of the suggested control is discussed using simulation results.

2. The Grid Connected Photovoltaic System

The proposed scheme, given by Figure.1, comprises a 2kW PV array coupled to the electric network through two converters. By tracking the reference voltage estimated by the MPPT controller, the chopper assures the impedance adjustment between the PV and the grid side.

The second part of the studied system comprises the DC link and the converter that is responsible for transferring the PV generated power into the network. The DC/AC converter acts as a regulator assuring a considerable power coefficient.

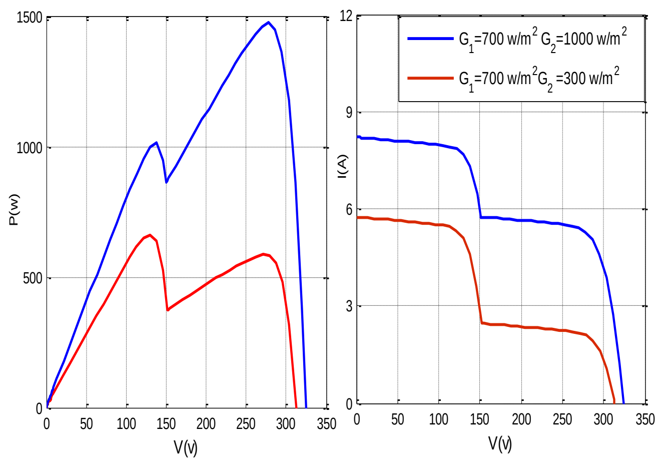
2.1. Shaded PV system model

The studied system comprises two PV array connected in series where one of them is shaded, each of which consists of 5 modules where each one contains 54 serial cells delivering under uniform climatic situations 2000W.

Partial shading results when the PV array is exposed to different radiations, the system's electrical performance willbe based on the cells specifications as well as the irradiation's conditions. In fact, the shaded modules utilize an amount of the generated power and behave as load. This influences on the general power production and can engender hot spot problem. Therefore, additional bypass diodes are used to avoid the self-heating of PV modules. Many researcheshave been performed to implement the photovoltaic model. The mathematical model of a solar module with N_s series cells is given by the equation below:

$$I_{pv} = I_{ph} - I_0(exp(V_{pv} + N_s R_s I_{pv} / N_s V_T) - 1) - V_{pv} + (N_s R_s I_{pv} / R_{shg}) \quad (1)$$

The system is simulated under different irradiations of G1 and G2 .The I-V and P-V characteristics, given inFigure 2,accentuate the role of the second generator's illumination. In fact, it influences on the PV general aspect particularly at the second peak.



(a) (b)

Fig.2. The global maximum position
(a) I-V characteristic (b) P-V characteristic

Figure 3 gives the P-V response a shaded PVG exposed to both G_1 =1000W/m^{2}and G_2 =500W/m^2.The inflexion point Iis the intersection of the P-V characteristic of a PVG exposed to a uniform irradiations and the shaded photovoltaic generator (PVG) response.

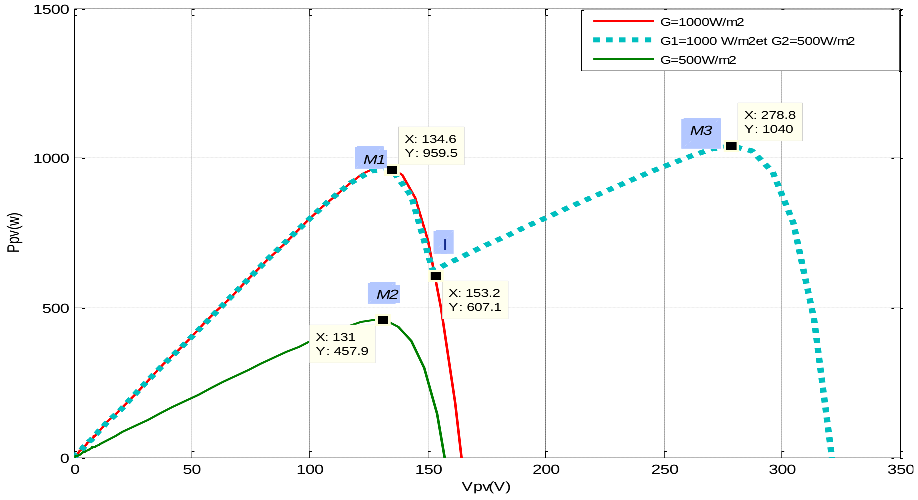


Fig.3. The shaded PV characteristic

M1 is the local maximum and *M3* is the global one. In fact*M3* is obtained by dragging the P-V curve for G=500W/m^2 to the point I, and the relationship between the different MPP is given by (2).

$$P_{pv}(M_2)+P_{pv}(I)=P_{pv}(M_3) \quad (2)$$

2.2. MPPT techniques

Numerous approaches have been used to track the MPP. In the present study, the FLC and the GA techniques are developed.

2.2.1. Fuzzy controller

The conventional MPPT methods face some problems as oscillating around the MPP and taking a long time to obtain the steady state. To ameliorate the PV response, many researchers [10] have developed FLC strategy for PV MPPT since the fuzzy logic technique is considered as a model free method, treating imprecise inputs and controlling non-linear systems.

The FLC scheme includes different parts: the fuzzification interface, the inference rules and the defuzzification interface.

During the fuzzification stage, the conversion of numerical inputs into linguistic variables is assured using seven fuzzy levels. Variables E and ΔE, expressed by equations (3) and (4) ,are proposed as input variables, where P (n) and V (n) represent the PV output power and voltage at the sampling instant n.

$$E(n)=\frac{P(n)-P(n-1)}{V(n)-V(n-1)} \quad (3)$$

$$\Delta E(n)=E(n)-E(n-1) \quad (4)$$

The specific input factors' memberships functions are given in Figure 5(a) and Figure 5(b) respectively.

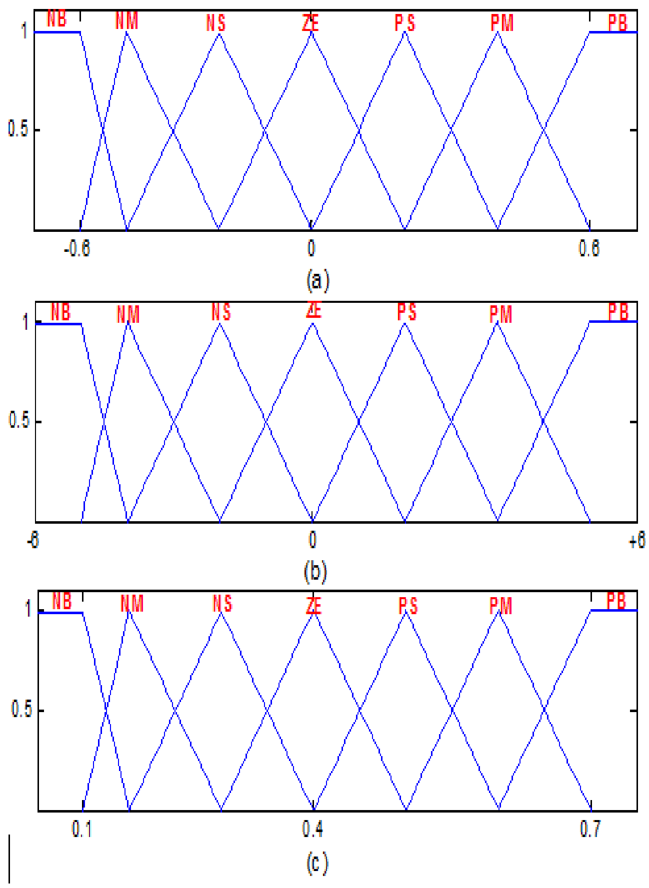


Fig.5. Membership functions of (a) input variable $E(n)$ (b) input variable $\Delta E(n)$ (c) output variable α .

In the present work, the FLC inference method requires 49 fuzzy rules presented in Table 1. The required converter duty cycle is found by applying these specific rules.

As an example control rule in Table 1: if $E(n)$ is PB and $\Delta E(n)$ is PB then α is ZE. During the defuzzification process, FLC output is transformed to a numerical output via the membership function, shown in Figure 5 (c).

Table1. The fuzzy controller's forty-nine rules

α	$E(n)$							
$\Delta E(n)$		NB	NM	NS	ZE	PS	PM	PB
	NB	ZE	ZE	ZE	NB	NB	NB	NB
	NM	ZE	ZE	ZE	NM	NM	NM	NM
	NS	NS	ZE	ZE	NS	NS	NS	NS
	ZE	NM	NS	ZE	ZE	ZE	PS	PM
	PS	PM	PS	PS	PS	ZE	ZE	ZE
	PM	PM	PM	PM	ZE	ZE	ZE	ZE
	PB	PB	PB	PB	ZE	ZE	ZE	ZE

2.2.2. Genetic controller overview

In the case of a partially shaded system with multiple MPP on the PV characteristic, classical MPPT algorithms are unable to track the GMPP. In this section, and in order to alleviate the problems associated with shaded PVG as discussed in the above, a GA technique is proposed.

A genetic algorithm (GA) is a complete search scheme depending on nature evolution mechanism.Several proprieties make GA a robust and data-independent technique as it starts with a population of points instead of a particular candidate when optimizing a fitness function [11]. The flow chart given by Figure.6 describes the different steps of this evolutionary technique.

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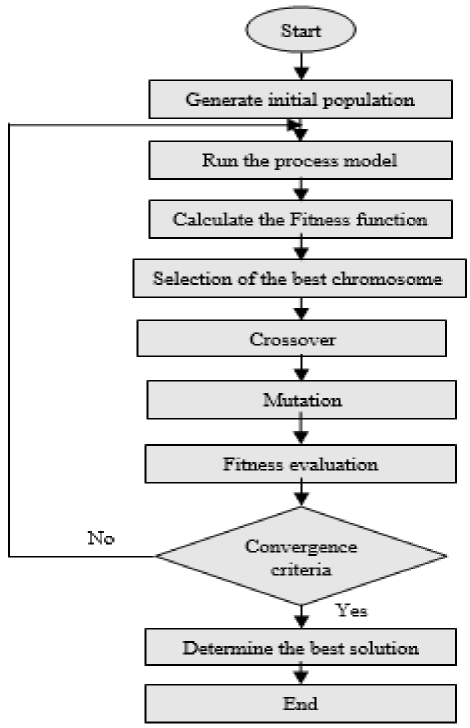


Fig. 6.The basic step of GA

The search technique of the GA includes three essential operators: *selection*, *crossover* and *mutation*. During the selection procedure, a chromosome is chosen from the present generation's candidates in accordance with its fitness and involved it in the next one; Crossover step groups two chromosomes to generate a new child while the mutation process assures the genetic diversity and seeks the stochastic variability of GA for faster convergence

2.2.3. Application of GA algorithm for MPPT

For the studied MPPT, the required output voltage at iteration k reflect the chromosomes position.

$$X^k = V^k \tag{5}$$

The considered population is composed by four chromosomes parents which are applied successively. Their initial positions are defined as:

$$[parent1, parent2, parent3, parent4] = 2V_{co}[0.8\ \ 0.6\ 0.4\ 0.2] \tag{6}$$

Where V_{co} *is* the open circuit voltage of the PV array. The generated power Ppvis considered as the algorithm's fitness. Based on eq (6), the crossover stage combines two chromosomes *parent*s to produce a chromosome*child*, for each iteration *K*.

$$\begin{cases} child(K) = r.parent(K) + (1-r).parent(K+1) \\ child(K+1) = (1-r).parent(K) + r.parent(K+1) \end{cases} \tag{7}$$

Where *r* is a random number $r \in [0\ 1]$.

The expression (8) gives the ratio of the PV voltage and the boost converter's duty cycle α. The GA parameters are illustrated in Table 2.

$$\alpha^k = 1 - \frac{child^k}{V_{co}} \tag{8}$$

Following the variation in operating conditions, the GA algorithm is modified in order to search the new MPP by reinitializing the first population whenever a condition change is deducted. The algorithm is initialized when these equations are satisfied:

$$\begin{cases} \left|V_{pv}(k+1)\right| \langle -\Delta V \\ \dfrac{P_{pv}(k+1) - P_{pv}(k)}{P_{pv}(k)} > \Delta P \end{cases} \tag{9}$$

Table2. The parameters of the proposed GA

Description	Parameters
Number of population	4
Mutation probability	0.1
Crossover probability	0.9

2.3. PQ inverter

The DC/AC converter interfaces the photovoltaic source with the power structure. It behaves as a power controller between the DC-link and the grid by assuring the regulation of the amount of active and reactive power injected in the utility network [12].
Its configuration is given by Figure 7.

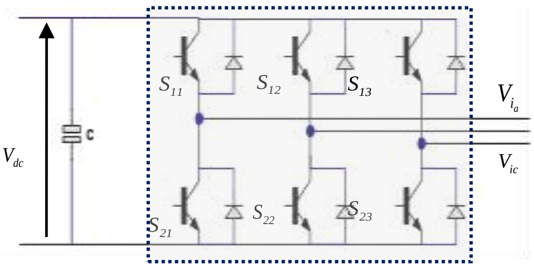


Fig.7. Configuration of the studied inverter

The converter's leg involves a group of two IGBTs connected with the same phase.

The two conditions for the switching variable g_k of each leg k are given by:

$$g_k = \begin{cases} 1, & (S_{1k} = 1 \text{ and } S_{2k} = 0) \\ 0, & (S_{1k} = 0 \text{ and } S_{2k} = 1) \end{cases} \quad k \in \{1,2,3\} \tag{10}$$

As ideal power switches are considered:

$$\sum_{j=1}^{2} S_{jk} = 1 \qquad k \in \{1,2,3\} \tag{11}$$

The inverter's voltages $V_{i_a}, V_{i_b}, V_{i_c}$ are related to the switching states S_{11}, S_{12} and S_{13} according to the following matrix :

$$\begin{bmatrix} V_{i_a} \\ V_{i_b} \\ V_{i_c} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ 1 & 2 & -1 \\ 1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_{11} \\ S_{12} \\ S_{13} \end{bmatrix} \tag{12}$$

2.4. The line-side converter's control

The grid dynamic model is expressed by:

$$\begin{cases} V_{g_d} = V_{i_d} - R_g i_{g_d} - L \dfrac{di_{g_d}}{dt} + wl_g i_{g_q} \\ V_{g_q} = V_{i_q} - R_g i_{g_q} - L \dfrac{di_{g_q}}{dt} - wl_g i_{g_d} \end{cases} \tag{13}$$

Where V_{i_d} and V_{i_q} are the d-q inverter voltage components, L_g and R_g are the grid inductance and resistance, respectively and i_{g_d} and i_{g_q} represent the d-q grid current components.
The active and reactive powers are determined from equations (14) and (15).

$$P = \frac{3}{2}\left(V_{g_d} i_{g_d} + V_{g_q} i_{g_q}\right) \tag{14}$$

$$Q = \frac{3}{2}\left(V_{g_q} i_{g_d} - V_{g_d} i_{g_q}\right) \tag{15}$$

The elementary structure of the grid side control is given inFigure.8; two PI controllers are proposed to regulate the injected power flow. A *d-axis PI regulator* assures the control of the active power, while a *q-axis PI regulator* regulates the reactive power.
The exchange of reactive power is not considered in this work, so the total power extracted from the PV system is transmitted to the network.

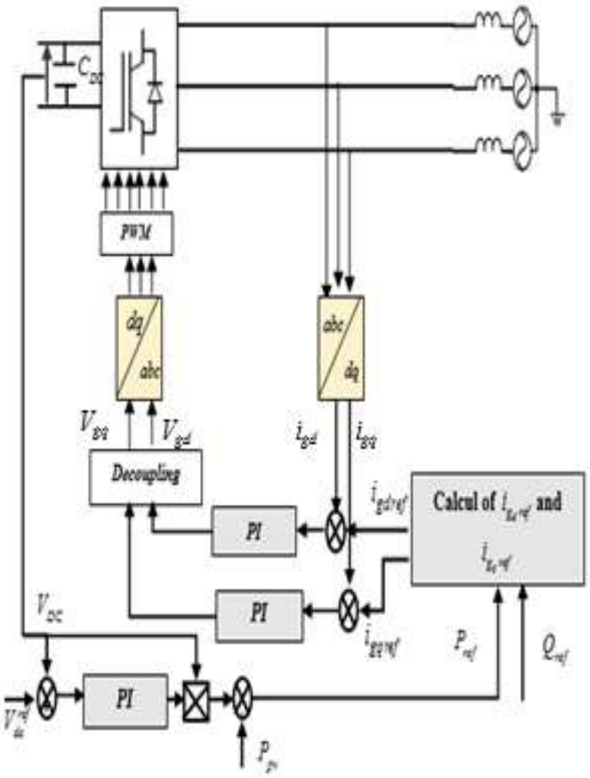


Fig.8. The different grid side control loops

3. Mismatch Power Loss

Due to partial shading, the mismatch losses (MML) occur between the interconnection of modules inside the PV array, it is calculated from the equation below:

$$MML = \frac{Maximum\ power\ of\ whole\ PV\ system}{\sum_{i=1}^{N} P_{max}(i)} \times 100 \quad (16)$$

The percent of MML reflect the generated power rate. The fact that the MPPT algorithm success to track the GMPP and do not stuck around the local maxima guarantees an increase in the rate of generated power.

4. Simulations of Proposed System

The proposed system is simulated under MATLAB/Simpowersystemsoftware and the parameters of the PV system and the electrical power system are given in Table 3.

Tables 3. Parameters of the system

Description	Parameters
Number of serial PV arrays in each module	5
Open circuit voltage of a single PV array	32V
short circuit current of a single PV array	8.21A
Reference solar radiation	1000W/m^2
Reference Temperature	25°C
Ns	54
DC/DC converter capacity	220 10^{-6}F
DC/DC converter inductance	1.8mH
DC bus capacitor	80010^{-6}F
Line resistance	1.25Ω
Line inductance	0.16 H

4.1. The behavior of the PV system under uniform conditions

Comparing the proposed MPPT techniques regarding their tracking capability at steady state, both the first and second PVG are simulated under standard conditions where the temperature is 25°C and the illumination is maintained at 1000 W/m^2 . The P-V characteristic is given in Figure 9, and Figure 10shows the response of the tracked power obtained from the studied MPPT techniques .The drawback of FLC algorithm is that, the system track the maximum with a value inferior to the MPP one giving rise to the waste of the available power.

Furthermore, the response of the FLC based controller presents oscillations around theoperating point even at steady state.The GA response presents also much smother signal with less fluctuations. Such fact is accentuated by acomparative performance studybased on three performance indices: the Mean Squared Error (MSE), the Mean Absolute Error (MAE) and the Mean Percentage Error (MPE).

The results are summarized in Table 4.

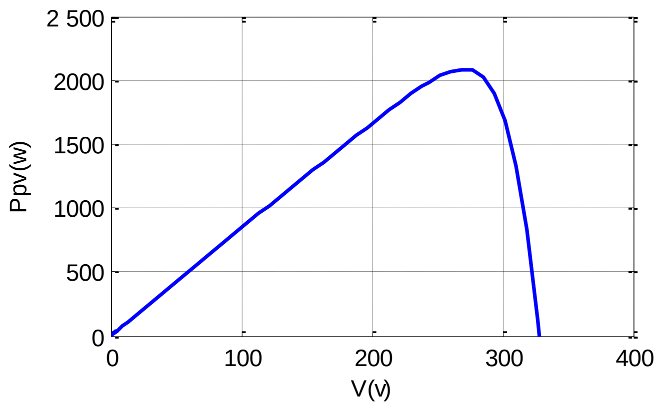


Fig.9. P-V characteristic

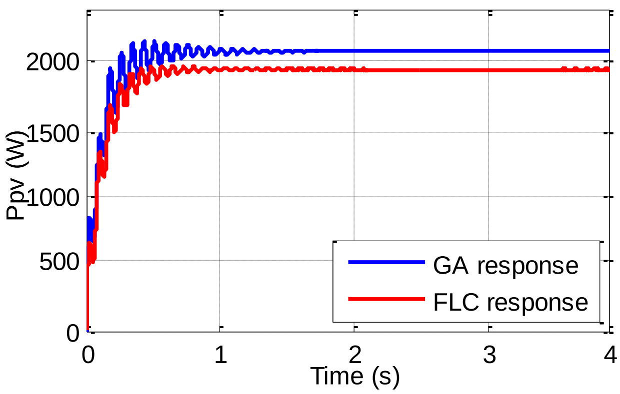


Fig.10. PV Power response

As confirmed by the error rate, the GA based MPPT approximates with a great accuracy the maximum power extractable from PV system simulated under uniform conditions

Table 4. Performance comparison

	MPE(%)	MAE(%)	MSE(%)
GA	0.0006	1.24	0.007
FLC	0.0010	2.39	0.030

4.2. The behavior of the system under partially shading conditions

To test the robustness of the studied algorithms a series of tests was performed underPSC. The simulation test consist in variying the first PVG illumination G_1 and keeping the second one constant(G_2=500w/m^2) as illustrated in Figure 11 and The P-V curves of the PV array are shown in Figure 12 .

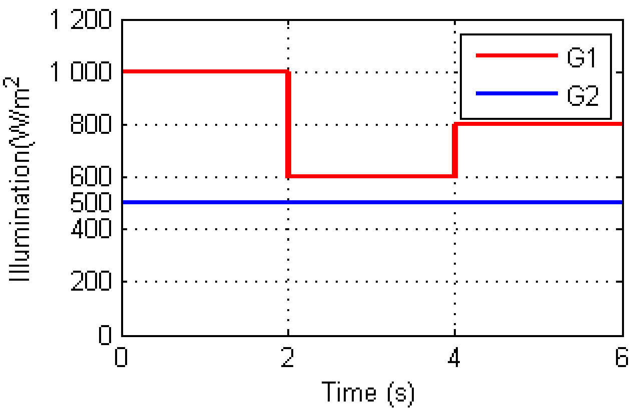


Fig.11. Illumination variation

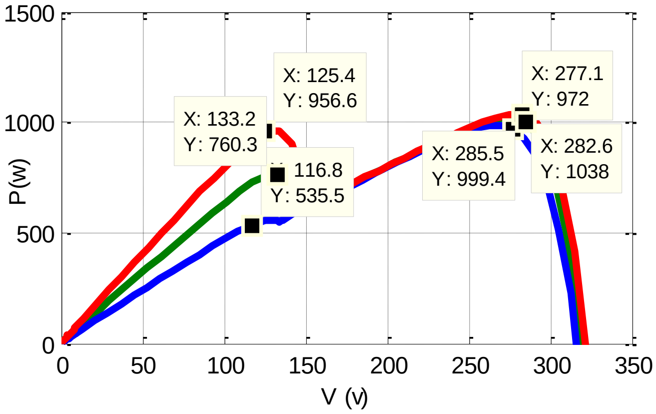


Fig.12. P-V characteristics

To compare the studied techniques performances, the simulations were executed in similar conditions. The response of the different studied MPPT techniques, given by the Figure 13, is valuated under rapidly changing weather conditions and their MML percent is illustrated in Table 5.

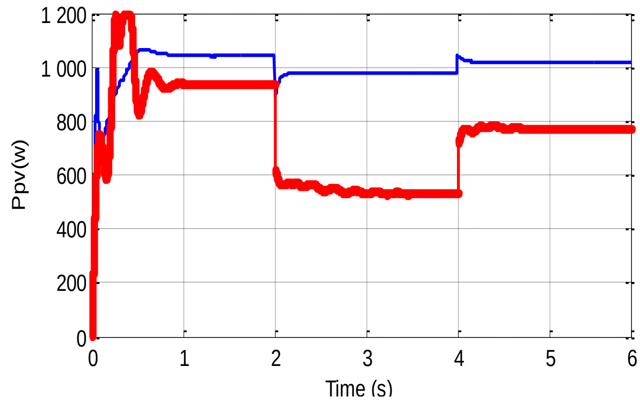


Fig.13. Generated power response

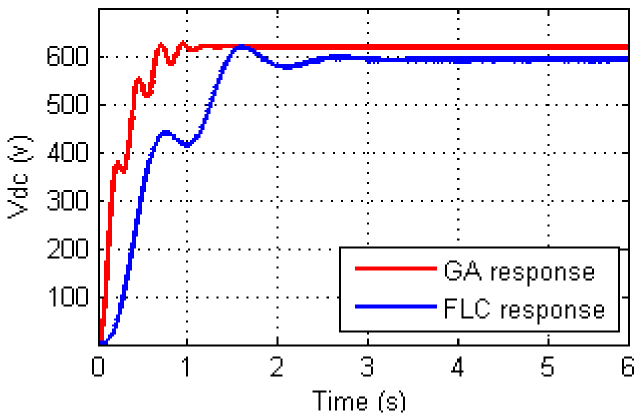
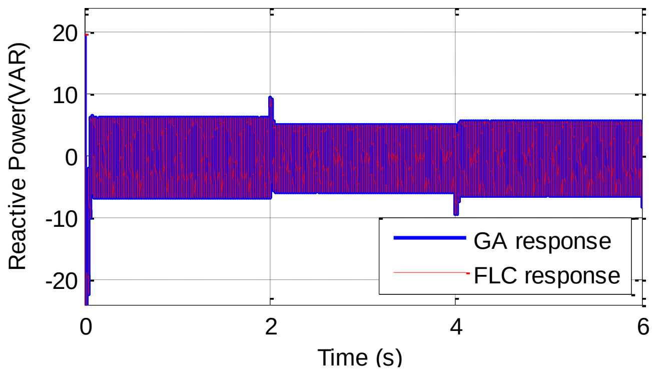


Fig.14. Bus voltage response

During the first 2seconds the GM of the P-V characteristic is equal to 1038W and the LM is 960W. The Generated power response show that the GA caught the global peak while the FLC stuck around the LM. So in this case the MML for GA is 1038/(1038+960)=51.9%, while FLC technique one is 960/(1038+960)=48.05% . It's clear that following the use of GA algorithm the generated power is 7.5% greater than the generated power reponse to the FLC.It can be deduced that GA track the MPP faster than the FLC algorithm since it reaches its target at 0.723 s, while the FLC based tracker requires more time (1 s) to reach the local maximum.

During the next period (2-4s), the radiation of the first PVG is 600W/m^2 . It's shown from the different techniques response that the GA caught the global peak which is 980W and the FLC truck the local peak with the power of 554W. The studied technique based on GA algorithm guarantees a generated power 43% greater than the power generated from FLC technique. Finally, during the last period and next to the variation of the first PVG radiation to 800W/m^2., the P-V charactristic present a GM equal to 980W and the GA success to truck it while the FLC stuck around the LM, so the MPPT based on GA increases 22.5% the generated power transmitted to the grid .Furthermore, comparing the studied methods with respect to complexity of implementation, both the GA and FLC represent a complex approaches, however, since theselection of the FLC membership functions and the fuzzy rules require excellent knowledge of the system the implementing complexity of the FLC is higher.

Next to the application of different MPPT techniques, the response of the direct currentDC link voltage regulation for PI controller while coupling the PV system with the network is given by Figure 14. The grid current response investigation enhance the inverter control effectiveness as confirmed by Figure 15.The Figure 15(c)gives the response of the grid voltage for different methods under study. As confirmed by the active and reactive power flow amount ,illustrated in Figure 16and Figure 17 respectively, the allure of the grid injected active power is very close to the generated one and the reactive power oscillates around zero which demonstrates the inverter control loops robustness.

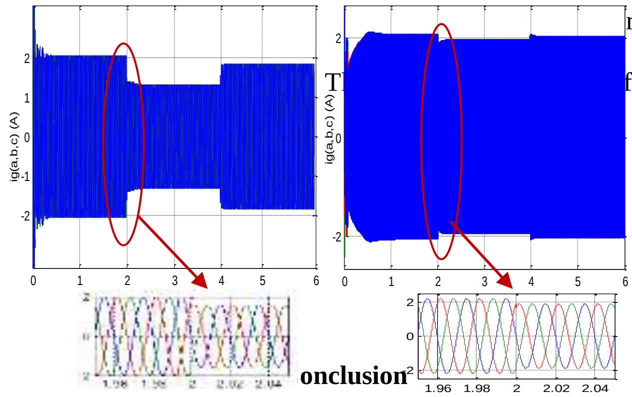


r response

T

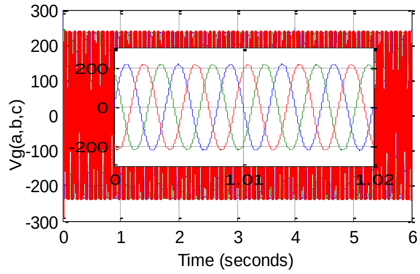
ferent technique

	(0-2)s	(2-4)s	(4-6)s
GA	51.9%	63.89%	56.32%
FLC	48.05%	36.11%	43.68%



onclusion

(a) (b)



(c)

Fig.15. Grid current and voltage responses (a) FLC grid response (b) GA grid response
(c) Voltage response for FLC and GA methods

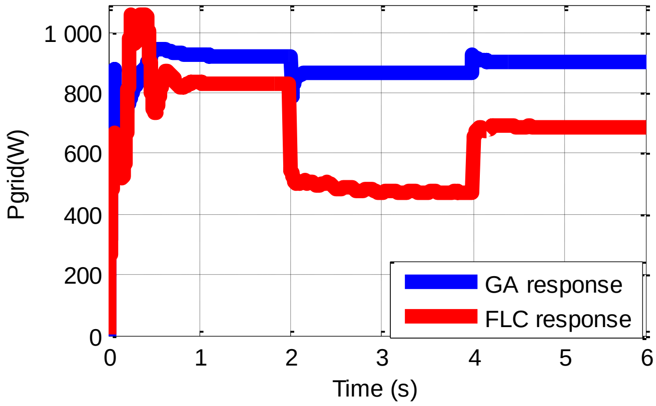


Fig.16. Active power response

The FLC method is unable to deal with PSC. To mitigate this limitation, a GA based MPPT is proposed in this work for the partially shaded grid-connected PVgenerator. The FLC and the GA method have been compared based on, both, steady state and under PSC responses. First, the comparison of the studied methods, concerning their tracking ability at steady state, demonstrates that the GA method extracts with a great accuracy the PV system's generated power with lower power percentage reduction compared to the other technique under study. Moreover, simulation results emphasize the developed GA technique efficiency under shade conditions. The GA based MPPT follows efficiently the GM under all operating states while the FLC techniques stuck around the first maximum encountered. Furthermore, the proposed GA approach is less complex and provides better dynamic and steady state performances.The response of the transmitted power flow with the network and the injected voltage and current allure demonstrate the grid side control's effectiveness.

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