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# SOLVING PROBLEM OF PARTIAL SHADING CONDITION IN A PHOTOVOLTAIC SYSTEM THROUGH A SELF-ADAPTIVE FUZZY LOGIC CONTROLLER

**H. Chekenbah** [1,*] **A. El Abderrahmani** [2] **A. Aghanim** [1] **Y. Maataoui** [1] **R. Lasri** [1]

*1. Laboratory of Sciences and Advanced Technologies FPL, University of Abdelmalek Essaadi, Larache, Morocco,*
*hamid.chekenbah@gmail.com, aghanimamina21@gmail.com, maataoui.yassir@gmal.com, rafik.Lasri@gmail.com*
*2. Computer Science, Signals, Automation and Cognitivism Laboratory, Department of Computer Sciences, Dhar-Mahraz Sciences School, University of Sidi Mohammed Ben Abdellah, Atlas-Fez, Morocco,*
*abdellatif.elabderrahmani@usmba.ac.ma*
**. Corresponding Author*

**Abstract-** In this paper, a new technique of global maximum power point tracking (G-MPPT) is introduced, where a Fuzzy Logic Controller with self-adapting output gain is used to solve the partial shading condition (PSC) problem. The gain adaptation is based on the study of the β parameter and applies only in the case of the presence of PSC to ensure stable operation under homogeneous weather conditions. The design of this tracker takes into account simplicity of implementation, flexibility, high performance, resistance to disturbances while guaranteeing better efficiency of about 100% under standard conditions or even in the presence of PSC. The performance of the presented command has been assessed by simulation in Matlab-Simulink and the gathered results are compared with that obtained by the conventional Perturbation and Observation (Perturb and Observe, P&O) controller. Different degrees of PSC with different distributions have been studied, the given results show the inability of the conventional P&O command to differentiate between the local and the global maximum power point (MPP) which significantly decreases its efficiency. On the other hand, the adaptive technique proposed presents a better yield in the absence and even in the presence of PSC. A quantitative study has been carried out and shows that the difference between the performances of the simulating techniques can reach up to 41.22% in favor of the presented adaptive Fuzzy Logic Controller.

**Keywords:** Partial Shading Condition, Global Maximum Power Point, MPPT, Fuzzy Logic Controller, Photovoltaic.

## 1. INTRODUCTION

Renewable energies assume significant importance in most development plans around the world. Despite of the challenges faced by humanity. Due to the growing demand for electricity, and the effect of polluting sources of energy on the environment. Photovoltaic solar energy (Photovoltaic, PV) is considered the most demanded source of renewable energy in the world, thanks to its remarkable advantages. Indeed, this source of energy is sustainable, non-fossil, does not require frequent maintenance, is free, available worldwide, and emits no noise [1]. Despite these advantages, this source of energy faces some challenges especially in the task of transferring the energy produced by the PV generators to the load, since it not only depends on weather conditions but also the nature of the load supplied by this generator. In fact, to a given value of PV generator power, corresponds a single value of the load (resistive for example), on which the operating power-point of the system will be maximum (Figure 1). It's called the optimum load of the PV generator.

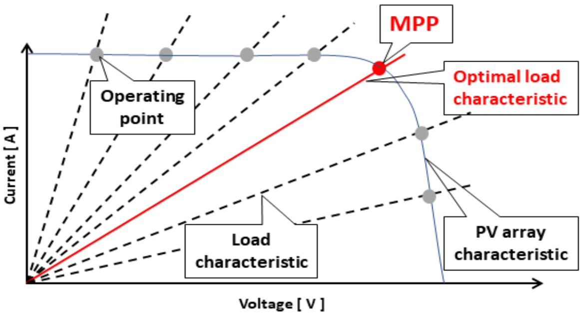

Figure 1. Direct connection between a PV generator and a load [28]

However, PV generators are typically designed to per a wide range of loads and even use variable loads such as batteries. This makes it mandatory to use a maximum power point tracking to ensure the transfer of all the produced energy by the PV generators. In the literature, we note that this area of PV system optimization has attracted a big interest from researchers for several years, and several techniques have been proposed which can be classified into two broad categories:

- Conventional techniques: generally based on the study of the photovoltaic $P(V)$ and $I(V)$ characteristics, such as the

Perturb and Observe commands [2], [23] which are the most used thanks to their simplicity. Incremental Conductance (Incremental Conductance, IC) [3], [24], Fractional Open-Circuit Voltage or Short-Circuit Current [4], [5], and the Hill Climbing method [6], [25].

- Intelligent techniques: such as Neural Networks, Fuzzy Logic Controllers [7], [27], and Particle Swarm Optimization [8], [26].

PV plants are usually installed in populated areas surrounded by building trees and others, these laters can lead to the phenomenon of partial shading condition. This aspect causes the appearance of several maxima on the characteristic curves of the PV generator [11], which makes tracking the true MPP (Global MPP) a difficult task. Especially for conventional techniques which stand on the direct voltage and power mensuration of the photovoltaic generator, such as P&O, IC, and Hill Climbing. Because these techniques are not able to differentiate between the global MPP (G-MPP) and the Local MPP (L-MPP).

Many studies are effectuated on the influence of the PSC phenomenon on the performance of PV systems, and they have shown that the presence of PSC leads to a remarkable decrease in the system efficiency which can reach up to 70% in systems that use conventional MPPTs [9]. This makes the design of more sophisticated trackers to overcome this problem of PSC. Meanwhile, in [10], a two-step technique, on which the authors used the adaptive β technique in the transient state, and the Zero Oscillation P&O technique in the steady-state. This method reduces the tracking speed and avoids the oscillation phenomenon. Some changes on the P&O technique made by the authors to take benefit from its advantages and especially its simplicity of implementation. We found for example in [11-13], a hybrid technique based on the study of the gradient sign of the characteristic *P-V*, on which the P&O technique is used with an adaptive step. The technique proposed in [11], allows obtaining a very short convergence time of about 100 ms. In [13], the authors showed that the use of a variable step overcomes the limitations mentioned in conventional P&O controllers. Because this technique reduces the oscillations around the MPP by nearly 75% and the tracking time by about 91.67%.

Among the smart techniques that show their efficiencies in the case of PSC, we find controllers based on Fuzzy Logic Controller (Fuzzy Logic Controller, FLC) [14],[15]. In [15] for example, a Fuzzy MISO (Multiple-Inputs Single-Output) controller is presented where the β parameter is used as an additional input variable. The use of the β parameter allows to reduce the number of fuzzy rules and improves the performance of the controller in the case of the occurrence of the PSC phenomenon.

These trackers face the challenge of detecting the existence of PSC. Among the proposed solutions, some authors set thresholds for the variation in power [16], others use thresholds for voltage and current variation [17]. However, due to the strong non-linearity of PV generators and the instability of weather conditions, the techniques proposed in [16], [17] do not give a reliable decision on the presence of PSC, especially, during a fast switch of weather conditions. To deal with this kind of problem, some researchers [18] have used timers to make a comparison between the actual variations of the approved parameters (variation of power, current, or voltage), and this comparison is carried out at discrete and periodic instants. This technique avoids the problem of confusing rapidly changing weather conditions and the phenomenon of PSC. On the other hand, it leads to an useless increase in execution time due to periodic interruptions in the case of stable weather conditions (steady-state).

In [9], [17], a double condition to verify the existence of PSC has been used. In particular, they used the conventional IC technique to follow the MPP in the absence of PSC. Moreover, in the case of PSC, the increment step of the IC command is replaced by a linear function that allows the operating point to be moved in the vicinity of the G-MPP. Subsequently, the conventional IC technique is used to track this G-MPP. In [19], we find a two-step technique based on the modification of the β parameter. The first step consists of determining the existence of PSC, while the later step is to track the true MPP. This technique has a short response time since it does not require the use of thresholds or interrupts.

In this article, a Self-adapting Fuzzy Logic Controller is used for tracking the G-MPP in a PV system. The proposed methodology uses both the parameter β to detect the existence of the phenomenon of PSC, and a Fuzzy Logic Controller with adaptive gain to follow the overall MPP. The rest of this paper is structured as follows: in the section 2, we find modeling of a photovoltaic array under homogeneous meteorological conditions, and in the case of PSC. Section 3 contains a description of the proposed technique in details. Various simulations and quantitative studies were presented in section 4. Finally, a conclusion of this work is done and presented in the last section.

## 2. MODELING OF A PHOTOVOLTAIC SYSTEM

### 2.1. Under Uniform Irradiation

The PV cell is the basic component of all PV systems, its role is to convert incident solar energy into electrical energy through the photovoltaic effect. It is a very low power source of energy (on the order of a few Watts). However, most electrical applications require high powers to meet the needs of consumers. for this purpose, PV cells are arranged in series and in parallel to build useful photovoltaic modules. These PV modules are non-linear components and are sensitive to several criteria such as weather conditions, nature of the connected load, adaptation technique between the GPV and the load adopted, as well as the phenomenon of PSC probably caused by trees, clouds, or even buildings. This makes modeling a PV system quite a complicated process. In this work, to model the PV cell, we have chosen the model with a single diode [20] shown in Figure 2.

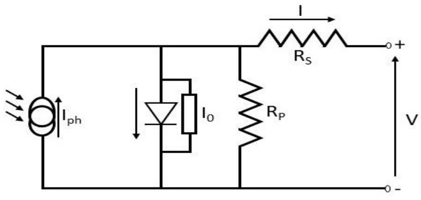

Figure 2. One diode model of a PV cell [20]

According to Figure 2, the characteristic $I(V)$ of the photovoltaic cell can be expressed by Equations (1) and (2) [20].

$$I = I_{ph} - I_{S0}.(e^{\frac{V+IR_S}{\alpha V_T}} - 1) - \frac{V+IR_S}{R_P} \quad (1)$$

$$V_T = \frac{K.T}{q} \quad (2)$$

where, $I_{S0}$ represents the reverse saturation current, $\alpha$ is an ideality factor. RS and RP are respectively the series and parallel (shunt) cell resistance. The photovoltaic module characteristic (composed of $NS_{cel}\times NP_{cel}$ photovoltaic cells) can be deduced from Equation (1) by entering the number of cells arranged in series ($NS_{cel}$), and the number of strings used ($NP_{cel}$) as shown in Figure 3.

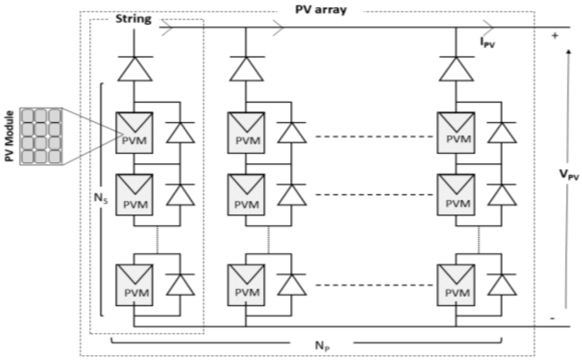

Figure 3. Photovoltaic array [14]

Photovoltaic modules are also arranged in series and in parallel to form photovoltaic arrays. Equation (3) describes the characteristic $I$-$V$ of a PV array made up of $N_S\times N_P$ PV modules [14].

$$I = N_P(I_{ph} - I_{SO}(e^{\frac{V+IR_S}{\alpha V_T N_S}} - 1) - (\frac{V+IR_S}{N_S.R_P})) \quad (3)$$

From Equation (3), it can be seen that the characteristics of such a photovoltaic array strongly depend on the irradiation and the temperature of the photovoltaic cells. This explains the non-linearity of the characteristic curves of the PV array.

### 2.2. Under Partial Shading Conditions

Under identical conditions (homogeneous distribution of irradiation over the entire surface of the PV system), the curve $P$-$V$ in figure 4 presents a single maximum called the MPP. But, in heterogeneous conditions (partial shading for example), several maxima appear in this curve, so there are local maxima and a single global maximum power point (Global Maximum Power Point, G-MPP) (Figures 4-5).

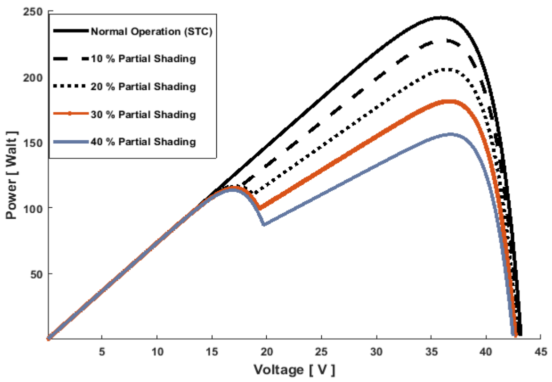

Figure 4. $P(V)$ characteristic of a photovoltaic generator under PSC

The presence of local maxima leads under certain conditions to non-optimal operation of the PV system, especially when using conventional MPPT. If we take the case of Figure 5 for example, where the operating point is close to the first LMPP, this point can be deduced from the intersection between the photovoltaic array characteristics and the load characteristic. In this case, the use of a conventional MPPT (P&O for example) causes the system to operate in the nearest MPP (Figure 6), which is not the real MPP G-MPP.

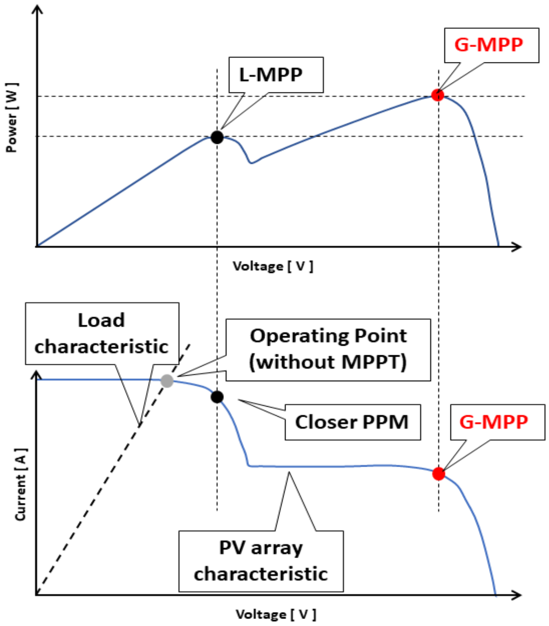

Figure 5. Local and global MPP

To overcome this issue of confusion between L-MPP and G-MPP, in this work, an adaptive multiple inputs and single-output (MISO) Fuzzy Logic Controller is used for tracking the G-MPP in real-time. The inputs of this controller are the variation of the power and the variation of the voltage between the terminals of the PV array. The output is the variation of the duty cycle which is used to control a Boost converter. A decision block is associated with the fuzzy controller to vary the gain at the output of this controller. This block uses the β parameter to detect the existence of the PSC. In the case of the absence of the PSC, the value of gain would be equal to 1 and the controller works like a conventional controller, and in the case of the detection of the PSC, the value of gain is replaced by a linear function to return the operating point toward the vicinity of the G-MPP.

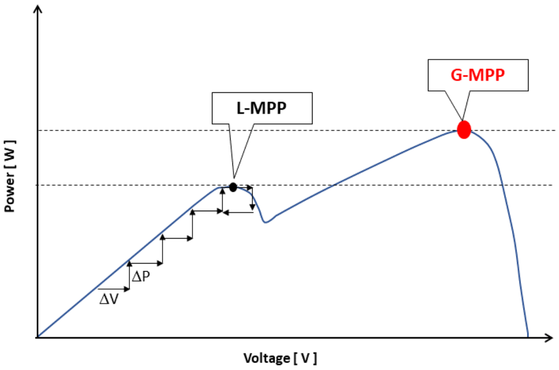

Figure 6. Operation principle of the P&O technique

## 3. PROPOSED TECHNIQUE

The technique proposed in this paper combines the advantages of using a Fuzzy Logic Controller, especially its flexibility and its possibility of self-adaptation, and the use of the β parameter. This parameter helps to go from the study of a system that presents a strong nonlinearity to the evaluation of an equivalent linear model [19]. This method is used for the first time in [21], and it has presented important results, which explains the use of this technique by many researchers [10], [15], [19], [22].

As a first step, this parameter is analyzed to limit these possible values in a homogeneous meteorological condition, Table 1 summarizes the results obtained. Note that this parameter can be limited between two values $\beta$_min = -916.6 and $\beta$_max = -181.7.

Table 1. Beta parameter variation

| | $T$ = 5 °C | $T$ = 25 °C |
|---|---|---|
| $G$ = 1000 W/m$^2$ | -480.7 | -916.7 |
| $G$= 100 W/m$^2$ | -886.6 | -181.7 |

When a PV array is consisting of m photovoltaic modules, the process of tracking the actual MPP can be replaced by an equivalent model on which the tracker operates as a simple MPPT for a single PV module [19]. The beta expression for these equivalent modules is described by Equation (4) [19]:

$$\beta_{eq} = \ln\left(\frac{I_{array}}{Veq}\right) - c.V_{eq} \tag{4}$$

where, $c = q/(NS.\alpha.K.T)$ and $V_{eq}$ is the equivalent voltage of the key model responsible for the position of the G-MPP in the characteristic $I$-$V$ [19]. This voltage can be expressed by equations (5) and (6) [19].

$$V_{eq} = V_{array} - (n-1).V_S + (m-n).V \tag{5}$$

$$V_S \approx \frac{V_{MP,STC} - V_{OC,STC}}{I_{MP,STC}}.I_{array} + V_{OC,STC} \tag{6}$$

where, $V_{MP,STC}$, $V_{OC\text{-}STC}$ and $I_{MP\text{-}STC}$ respectively represent the maximum voltage, the open-circuit voltage, and the maximum current under standard test conditions, $I_{array}$ is the current of the PV array, and $n$ depends on the number of PV modules ($m$) and the open-circuit voltage [19].

The value of $\beta$ is measured instantly, and the current value is evaluated at each instant, if this value is located in the range [$\beta_{\min}$, $\beta_{\max}$], it means that the operating point is close to the true GMPP, the fuzzy controller, therefore, operates in this case as a conventional controller. Otherwise, where the instantaneous value of $\beta$ is outside the range [$\beta_{\min}$, $\beta_{\max}$], the output of the fuzzy controller will be determined according to Equations (7) and (8).

$$g = \begin{cases} -abs(k.(\beta(t) - \beta_{ref}), if\ \beta(t) > \beta_{\max} \\ +abs(k.(\beta(t) - \beta_{ref}), if\ \beta(t) < \beta_{\min} \\ 1, if\ \beta_{\min} < \beta(t) < \beta_{\max} \end{cases} \tag{7}$$

$$\beta_{ref} = (\beta_{\max} - \beta_{\min})/2 \tag{8}$$

where, $k$ is a normalization factor.

The internal structure of the FLC is described in Figure 7, and the set of fuzzy rules used are shown in Table 2. We adopted the Mamdani Min-Max type fuzzy inference system, with centroid defuzzification type. The diagram of the presented technique is summarized in Figure 8.

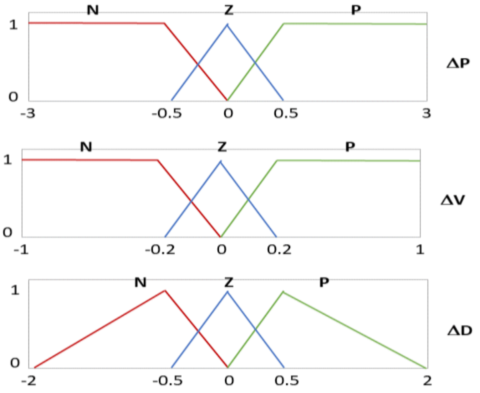

Figure 7. Structure of the fuzzy logic controller used

Table 2. Fuzzy logic controller rule base

| | | DV | | |
|---|---|---|---|---|
| | | NE | ZE | PO |
| DP | NE | NE | ZE | PO |
| | ZE | ZE | ZE | ZE |
| | PO | PO | ZE | NE |

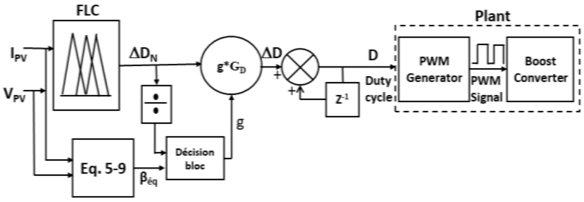

Figure 8. Diagram of the proposed technique

The parameters of the Boost converter are chosen to guarantee optimum operation of the latter at a switching frequency ($f_c$) of 10 KHz. The choice of these parameters is made while respecting the following two conditions:

- The value of the inductance is much higher than the critical inductance defined by (9) [12]:

$$L_C = \frac{(1-D)^2.D.R}{2\,f_c} \quad (9)$$

- The value of the capacitor must be higher than a minimum value defined by (10) [12]:

$$C_{\min} = \frac{V_0.D.R}{\Delta V_0.f.R} \quad (10)$$

where, $\Delta V_0$ is the ripple voltage.

By respecting the conditions mentioned in (9) and (10), the values used in the Boost converter are mentioned in Table 3.

Table 3. Main components specification for the boost converter

| Parameter | Value |
|---|---|
| Switching frequency | 10 KHz |
| Inductance, $L$ | 0.24 mH |
| Input Capacity, $C_{in}$ | 120 µF |
| Output Capacity, $C_{out}$ | 220 µF |
| Load, R | 25 Ω |

## 4. RESULTS AND DISCUSSIONS

To assess the performance of the technique presented in this article, several tests were carried out under varying operating conditions in the presence and even in the absence of the phenomenon of PSC. To do this, a PV array consisting of 3 PV modules arranged in series has been chosen, each PV module produces 60 W under standard test conditions. To simulate the phenomenon of PSC, we have adopted several scenarios in which the three PV arrays are used with different degrees of irradiation. Figures 9 and 10 present the simulation results obtained for two different cases:

- 1st case: 900 W/m$^2$ - 400 W/m$^2$ - 600 W/m$^2$
- 2nd case: 400 W/m$^2$ - 400 W/m$^2$ - 900 W/m$^2$

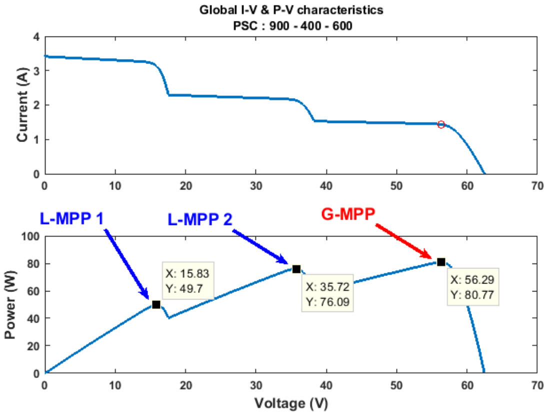

Figure 9-a. Global characteristics under partial shading (case 1)

From the obtained results of the simulation, it can be remarked that the adaptive Fuzzy Logic Controller presented makes it possible to follow the real MPP in the case of the presence of PSC. Indeed, the operating power point of the photovoltaic system in the case of PSC is certainly the Global MPP, regardless of the degree and the distribution of shading presented. It is also noted that this G-MPP is reached with minimal time and without major disturbance.

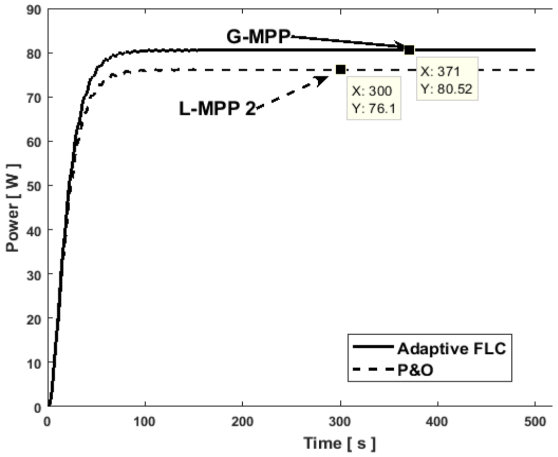

Figure 9-b. Simulation results of the presented technique and the conventional P&O commands (case 1)

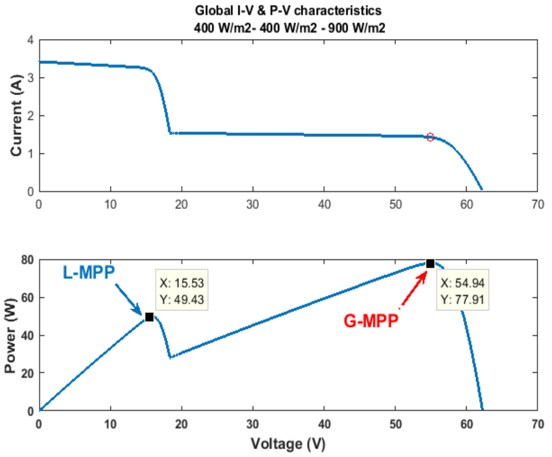

Figure 10-a. Global characteristics under partial shading (case 2)

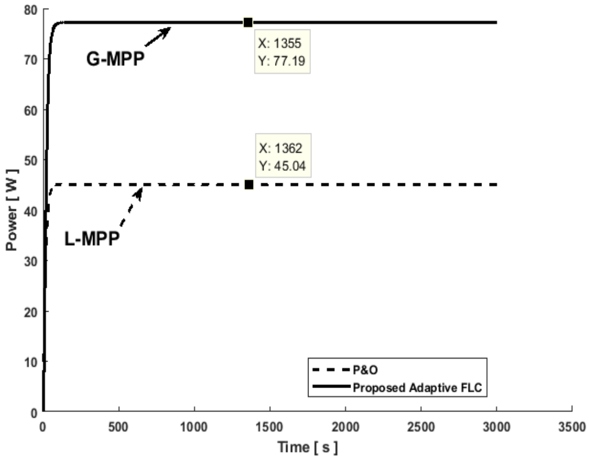

Figure 10-b. Simulation results of the presented technique and the conventional P&O commands (case 2)

To fully understand the advantages of the proposed technique, a quantitative study is performed, in which a comparison between the said technique and the conventional P&O techniques is made. Table 4 summarizes the results obtained.

Table 4. Quantitative comparison between the proposed technique and the conventional P&O technics

| PSC | Maximum Power Points (W) | | | | P&O | | Proposed MPPT | |
|---|---|---|---|---|---|---|---|---|
| | MPP-1 | MPP-2 | MPP-3 | GMPP (W) | Tracked power | Efficiency (%) | Tracked power | Efficiency (%) |
| STC | 178.7 | × | × | 178.7W | 178.1 W | 99.66 | 178.5 W | 99.88 |
| 900<br>400<br>600 | 49.7 | 76.09 | 80.77 | 80 W | 76.1 W | 94.21 | 80.52 W | 99.69 |
| 400<br>400<br>900 | 49.43 | 77.91 | × | 77.91W | 45.04 W | 57.81 | 77.19 W | 99.07 |
| 1000<br>400<br>700 | 45.44 | 88.14 | × | 88.14W | 85.23 W | 96.69 | 87.46 W | 99.22 |
| 1000<br>400<br>400 | 45.42 | 78.05 | × | 78.05W | 45.12 W | 57.80 | 77.29 W | 99.02 |

Table 4 shows that the flexibility of the studied technique does not influence its performance particularly under homogeneous conditions (in the absence of PSC), or even after the appearance of PSC. On the other hand, in the P&O control, it is not possible to distinguish between L-MPP and G-MPP, which leads to a remarkable decrease in the efficiency of the system.

## 5. CONCLUSIONS

In this work, a real-time Fuzzy Logic Controller with an adaptive gain is presented to track the MPP in a stand-alone PV system. Gain adaptation is used to solve the problem of the occurrence of the PSC phenomenon which causes a decrease in the efficiency of the MPP Tracker due to the appearance of local minima in the characteristic curves of the PV array. This adaptation is based on the study of the variation of the beta parameter. The simulation results showed the effectiveness of the proposed technique whether under homogeneous conditions or in the case of PSC. This technique has excellent performance over a wide power range and can be used on any type of PV panel because it does not require any predefined parameters on the PV modules used. Quantitative comparison was made between the presented technique and conventional trackers. The obtained results showed that this technique makes it possible to overcome the problem of PSC since it makes it possible to follow the real MPP (G-MPP) at all times whatever the degree and distribution of shading presented.

## NOMENCLATURES

### 1. Acronyms

| | |
|---|---|
| PSC | Partial Shading Condition |
| MMPT | Maximum Power Point Tracker |
| GMMPT | Global Maximum Power Point Tracker |
| P&O | Perturb and Observe |
| PV | Photovoltaic |
| L-MPP | Local Maximum-Power Point |
| FLC | Fuzzy Logic Controller |
| STC | Standard Test Conditions |

### 2. Symbols / Parameters

$I_{S0}$: The reverse saturation currents
$\alpha$: An ideality factor
$R_S$: The series resistance of the photovoltaic cell
$R_P$: The parallel (shunt) resistance of the photovoltaic cell
$NS_{cell}$: The Number of cells arranged in series
$NS_{cell}$: The number of strings
*STC*: Standard Test Conditions
$V_{MP-STC}$: The maximum voltage under STC
$V_{OC-STC}$: The open-circuit voltage under STC
$I_{array}$: The current of the photovoltaic array

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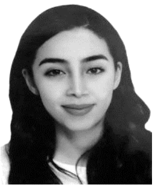
## BIOGRAPHIES

**Hamid Chekenbah** was born in Larache, Morocco, in 1979. He obtained his Master' degree in Embedded Systems from the Faculty of Science in Kenitra, Morocco in 2015. He is currently a Ph.D. student in the field of "Implementation of intelligent algorithms in control and regulation processes" at the Polydisciplinary Faculty of Larache, Abdelmalek Essaadi University, Morroco. His publications include a chapter, an article in an international journal and 4 conferences in the fields of complex systems. His research areas include design of intelligent systems, intelligent control, application of artificial intelligence to power system control design, control systems engineering, complex systems, and fuzzy logic control.

**Abdellatif El Abderrahmani** was born in Tafilalet, Morocco, in 1977. He received the Ph.D. degree in computer science from USMBA-Fez University, Morocco in 2012. He is currently a Professor of Computer Science at USMBA-Fez University. He is a permanent member of the LISAC laboratory and associate member of the Advanced Sciences and Technologies Laboratory at UAE University. His research interests include image-based rendering, augmented reality, camera self-calibration, 3D reconstruction, big data analytics, internet of things and cloud computing.



**Amina Aghanim** Was born in Fes Morocco, in 1995. She obtained the Master's degree in advanced technologies and Embedded systems, from Abdelmalek Essaadi University, FPL, Morocco in 2020. She is currently a Ph.D. student in the domain of fuzzy logic tuning of microwave filters.

**Yassir Maataoui** was born in Larache Morocco, in 1992. He received the Master's degree in Embedded Systems from the University of Abdelmalek Essaadi, FPL, Morocco in 2019. He is currently pursuing the Ph.D. degree at the Department of Electrical Engineering of The Multidisciplinary Faculty of Larache. His current research interests include electrical power systems, fuzzy logic controllers, power electronics, energy engineering, distributed generation, advanced control theory and electrical engineering.

**Rafik Lasri** was born in Larache, Morocco, in 1981. He received the Diploma of Advanced Studies DAS in 2007 and the Ph.D. degree in Design, Analysis and Applications of Intelligent Systems from University of Granada, Spain, in 2012. Currently, he is an Associate Professor at physics department of the Polydisciplinary Faculty of Larache, Abbdelmalek Essaadi University, Morocco. He published one research book, 2 book chapters, 18 research papers in different international conferences, 12 research papers published in various SCI and SCOPUS indexed international journals. His research interests include intelligent control, application of artificial intelligence to power system control design, fuzzy logic control, control systems engineering, machine learning, computational intelligence, soft computing, wireless computing and data mining.