Application of an adaptive fuzzy logic controller to optimize the performances of the P&O algorithm

Hamid Chekenbah	extsuperscript{1*}, Yassir Maataoui	extsuperscript{1}, Rafik Lasri	extsuperscript{1} and Larbi Choukri	extsuperscript{2}

	extsuperscript{1}Lab. STA, FPL, Abdelmalek Essaadi University, Morocco
	extsuperscript{2}Lab. CST, FST, Abdelmalek Essaadi University, Morocco

*hamid.chekenbah@gmail.com

Abstract. In this work, an Adaptive Fuzzy Logic Controller is studied to optimize the transfer of the power provided by a photovoltaic generator. The adaptation process is carried out online in two tasks: the adaptation of the rules consequences and the self-organization of the internal structure of the Fuzzy Controller. In comparison with two types of traditional controls, the performance of the controller studied is validated. The simulation results show that the controller studied makes it possible to reduce the response time by 3\% compared to the conventional controller, and minimizes the steady-state error by eliminating the phenomenon of oscillation around the PPM and that the proposed controller exhibits good behavior with a wide range of power.

1. Introduction

In most photovoltaic applications, the pursuit of guaranteeing the transfer of all the power generated by the Photovoltaic (Photovoltaic, PV) generators have attracted a big interest. For this purpose, the use of the maximum power point tracker becomes a necessity because of the likely mismatch between the maximum power point (Maximum Power Point, MPP) and the characteristics of the connected loads. On the other hand, PV systems exhibit strong non-linearity, and each shift in meteorological conditions caused a shift in the position of the MPP, making dynamic tracker design a necessity. In the literature, there are dozens of techniques for tracking the MPP.

Among these, we find techniques based on the return of power [1], [2]. In [1] for example, we find the method of perturbation and observation (Perturb and Observe, P&O), it's the most widely used owing to its ease of implementation, even if it presents difficulties concerning the coordination between the response time and the steady-state error. The conductance increment method was presented in [2], which is similar to the P&O method because they are both based on the PV generator voltage regulation technique by tracking the MPP to satisfy the following equation: $\frac{dP}{dV} = 0$. Among the conventional techniques used in the literature, we also find the escalation algorithm [3], the short-circuit current [4], the constant voltage tracking [5], and the incremental conductance algorithm [6].

On the other hand, smart techniques such as Fuzzy Control [7], Sliding-mode Control [8], and Neural-Network [9] were used. The fuzzy logic control algorithm has been widely used in nonlinear systems in general and in PV systems in particular. Thanks to the flexibilities they exhibit even in the absence of a precise mathematical model. Each of the aforementioned methods has high efficiency in the steady-state. However, these methods are lacking in unstable weather conditions especially when
these conditions change rapidly. This makes the design of adaptive maximum power point trackers a requirement (Maximum Power Point Tracker, MPPT). Adaptive Controllers are also utilized in PV systems to surmount the aforementioned restrictions concerning Conventional Controllers due to the non-linear nature of PV generators and their strong dependence on weather conditions. Among these methods is the Hill-Climbing (HC) Method [10] [11]. [11] Presents an association of the Subsection and Adaptive-HC technique.

The obtained results revealed that the presented controller has good results in the sense of response time, current ripple (13%), and voltage (3%). And in [10], an Adaptive-HC MPPT algorithm for PV systems is presented. In the design of this controller, the automatic adjustment topology has been presented in the form of linear formula. The results of the simulation demonstrate that this controller makes the tracking speed faster. Authors in some papers have improved Particle-Swarm Optimization (Particle-Swarm Optimization, PSO) based algorithms [12] [13]. [12] Introduces the Adaptive Inertial-Weight PSO algorithm, simulation results showed that the Adaptive Inertial-Weight PSO can reach MPP with minimum time and with good accuracy and also has strong robustness and reduced fluctuations near the MPP compared to the PSO algorithm.

In [13], we find the adaptive Chicken-Swarm Optimization (CSO) technique, this algorithm makes it possible to locate the global MPP in the case where the system is subjected to partial shading. On the other hand, an Adaptive-Step Perturbation algorithm is used in [14]. This method makes it possible to avoid the phenomenon of oscillation around the PPM and to obtain a rapid response in the transition regime. In this work, an MPPT based on a self-adaptive fuzzy logic controller is presented, on which the adaptation is carried out online and in two stages. The first step consists of a sanction/penalty type adaptation of the consequences of fuzzy rules. While in the second step, online self-organization of the internal structure of the FLC is applied. The rest of this article is ordered as follows. The design and modeling of the presented algorithm used in this comparative study are presented in section 2. Section 3 is showing the efficiency of the studied tracker by comparing the obtained simulation results with two other conventional controllers.

2. Proposed Algorithm

The algorithm proposed in this article focuses on the design of a Maximum Power Point Tracker centered on the integration of a Self-Adaptive FLC in a P&O tracker. The role of the Self-adaptive controller is to overcome the shortcomings noted in the conventional controller [15], especially during a rapid change in weather conditions. The goal of this work is to achieve a stable and robust tracker. Indeed, the validation criteria of such a controller are stability, dynamic response, steady-state error, robustness, and the power range.

2.1 Stability

Stability is the essential requirement when designing a controller, and for non-linear systems like PV systems, this criterion becomes very dominant because of the non-linearity of the PV generators and DC-DC converters often used in achieving an MPPT. An incorrect choice of parameters or operating frequency leads to a disturbance in the operation of the tracker.

2.2 Dynamic response

A good tracker must react immediately to the changes from operating conditions, be it the weather or plant operating conditions by tracking the new MPP.

2.3 Steady-state error

When the system reaches the MPP, the MPPT must operate the system exactly at this point to avoid the oscillation phenomenon as much as possible. This is impossible due to the continuous change in weather conditions, but a small fluctuation in the steady-state output power is acceptable.
2.4 Robustness
We must design an MPP tracker resistant to all types of disturbances that can disturb the functionality of the system.

2.5 The power range
As known, a successfully designed MPPT should perform well at different power levels, not just in small bands of irradiation and cell temperature.

3. Modeling
Figure 1 shows the diagram of the studied system; it contains a PV generator, a proposed MPPT, resistive load, and a DC-DC converter. The role of the Adaptive FLC is to determine at every moment the optimal increment step for the P&O algorithm.

![Schematic diagram of the studied solar system.](image)

4. Modeling of the Adaptive Fuzzy Logic Controller
An FLC has three essential parts: Fuzzification, Fuzzy inference, and Defuzzification.

4.1 Fuzzification
Fuzzification is a mechanism that transforms real values at the controller input into fuzzy values using the notion of the membership function (Membership Function, MF). In this work, the Mamdani type controller was used. The controller plant can be modeled mathematically by the differential equation (1) [19]:

\[ p(k+1) = h(p(k), p(k-1), \ldots, p(k-m), i(k), i(k-1), \ldots, i(k-n)) \]  \hspace{1cm} (1)

Where: \( p(k) \): represents the instantaneous output of the plant to be controlled, \( h \): is a continuous function, \( i \): represents the controller input, \( m \) and \( n \): set the order of the plant.

In this work, we have chosen triangular MF, a fuzzy T-norm product type inference, and a center of gravity is chosen for defuzzification. The Fuzzy Controller inputs are the Error \( E \) and the Change of the Error \( CE \) determined by (2) as showed in Figure 2. While the output is the value of the Perturb and Observe algorithm increment voltage. The inference rules are listed in Table 1.

\[ E = \frac{\Delta p}{\Delta V}, \ CE = E(k) - E(k-1) \]  \hspace{1cm} (2)

![Structure of the FLC.](image)

**Table 1. Fuzzy Inference.**

| CE | E | NegL | Neg | Zer | Pos | PP |
|----|---|------|-----|-----|-----|----|
| NegL | PP | Zer | PP | PP | PP |    |
| Neg | Zer | Zer | Pos | Pos | Pos |    |
To simplify the implementation of the controller studied, the input and output variables of the FLC are divided into five MFs and we only store the centers and base values of these functions.

4.2 Stage of Online adaptation of the consequences of the rule

In this part, an adaptation of the FLC rules consequences, as a sanction/penalty type is performed online according to (3) [17], this correction, is applied by evaluating the current state of the system.

\[
\Delta R_{i1i2...in}(t-\tau) = e_i(1 - \alpha_i(t-\tau)).E_i(t) = e_i(1 - \alpha_i(t-\tau)) \cdot (S(t-\tau) - O(t))
\]  

(3)

With: \(\tau\): represents the delay, \(\alpha_i(t-\tau)\): represents the degree of the activation of the rule at \((t-\tau)\) [19], \(S(t-\tau)\): is the required set-point at \((t-\tau)\), \(O(t)\): is the plant output, \(e\): is a normalization constant and \(R_{i1i2...in}\): are the consequences of the rule.

4.3 Stage of membership functions self-organization

The most complex step in designing a fuzzy logic controller is building its internal structure as well as formulating the fuzzy rule base. Indeed, the good design ensures the coverage of all values of the entry space (Figure 3), which therefore results in the perfect operation of the controller. On the other hand, the poor design of the controller structure, especially the positions and dimensions of the membership functions does not cover all the values of the input space (Figure 4). Consequently, this does not extract the correct response.

To overcome this problem, in this part, self-organization of the Fuzzy Logic Controller internal structure has been applied on which, the positions and dimensions of membership functions are self-organized online and in real-time. The displacement of the MFs is ensured by modifying the positions of its centers \((c_1, c_2... c_N)\) while the resizing is ensured by modifying the bases \((b_1, b_2... b_N)\) of the MFs.

![Figure 3. Bad construction of membership functions.](image)

![Figure 4. Good construction of membership functions.](image)

This online self-organization is centered on the technique presented by I. Rojas et al., [16], and adapted to the needs of our tracker to which we added a part of resizing membership functions according to (7 and 9). This operation aims to obtain at all times, an ideal internal fuzzy controller structure. This online self-organization is based on the assessment of square-error integral (Square-Error Integral, SEI) recorded inside control operation and which is given by (4) [17].
\[ ISE_k^l = \frac{1}{\delta_y^l} \left( \int e^2(t) dt \bigg|_{u_k(t) \in s_{k-1}^l} - \int e^2(t) dt \bigg|_{u_k(t) \in [s_k^l, s_{k+1}^l]} \right) \]  

Where: \( s_k^j \) represents the position of the \( j \)th MF, \( u_k \) represents the controller input and \( \delta_y \) represents a factor of normalization.

The first part of (5) counts the error in the case where the \( u_k \) is between the centers of MF’s \( s_{k-1}^l \) and \( s_k^l \), while the last part counts the error in the case where \( u_k \) is between the centers of MF’s \( s_k^l \) and \( s_{k+1}^l \). Consequently, the calculation of this integral makes it possible to determine the most active membership functions, which have a great contribution to the SEI. The assessment of the SEI is the basic criterion used in this part of the membership self-organization according to (5 and 6) as shown in Figure 5:

If \( SEI > 0 \):
\[
\Delta c_k^l = \frac{c_{k-1}^l - c_k^l}{2 ISE_k^l}, \quad \Delta b_k^l = \frac{\Delta c_k^l}{\rho_l}, \quad \Delta b_k^l = \frac{\Delta c_k^l}{\rho_l}
\]  

If \( SEI < 0 \):
\[
\Delta c_k^l = \frac{c_{k+1}^l - c_k^l}{2 |ISE_k^l|}, \quad \Delta b_k^l = -\frac{\Delta c_k^l}{\rho_l}, \quad \Delta b_k^l = +\frac{\Delta c_k^l}{\rho_l}
\]

Figure 5. Self-organization of Membership functions.

With: \( c_k^l \) is the center of the \( l \)th MF of the input \( u_k \), \( \rho_l \) and \( \Phi_k \) are the normalizations factors, \( b_k^l \) is the basis of the \( l \)th membership function of the input \( u_k \). \( \Delta c \) is used to redistribute the MF, while \( \Delta b \) has the role of resizing the MFs. To guarantee that at all times, at least two MFs are activated.

5. **Adaptive Fuzzy controller flowchart**

Figure 6 shows the flowchart of the proposed Adaptive Tracker.
Figure 6. Adaptive controller flowchart.

6. Results of the Simulation and Discussions

The designed tracker is simulated under different operating conditions to assess its effectiveness. Figure 7 and Figure 8 show the simulation results obtained in comparison with an MPPT-P&O commands and an MPPT-P&O improved by a Conventional FLC. According to the simulation results obtained from the trackers compared, we can note that the presented tracker has the best results whether in the permanent regime (Figure 8) or the transient regime (Figure 8). Moreover, this Adaptive Controller has a more stable response and allows us to track the MPP with almost zero oscillation (Figure 7-c and 8-c). It also reduces significantly the tracking time by 3% compared to conventional controllers. From the results presented in Figure 8, we notice that this controller has a good performance with a wide range of power.

7. Conclusion

In this work, a self-adaptive MPPT is studied to optimize the power transmitted by the PV generator. This tracker is produced using a self-adaptive Fuzzy Logic Controller integrated into the P&O algorithm. The adaptation process is carried out in two stages: an adaptation of the rules consequences and the self-organization of the internal structure of the Fuzzy-Controller. Finally, the controller studied is compared with the P&O command and the P&O command improved by a conventional Fuzzy Logic Controller. The obtained results of the simulation show that by using the tracker studied it is possible to optimize the power transmitted by the PVG. As seen in the simulation results, the response time reduced by 3%, increased the energy efficiency by 2% and eliminated the phenomenon of oscillation between the maximum power point in the steady-state by this tracker.

Figure 7. Simulation results under STC (1000 W/m², 25 °C).
**Figure 8.** Instant increase of irradiation from 300 W/m² to 700 W/m² and from 700 W/m² to 1000 W/m² in T = 25 °C.

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