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Design of an intelligent controller for improving the solar system efficiency

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Abstract

Ensuring the optimal performance of photovoltaic systems necessitates the development of a maximum power point tracker MPPT aimed at extracting the utmost power from the photovoltaic array. This study delves into the efficacy of a fuzzy logic controller compared to conventional controllers designed for tracking the maximum power point. The simulation model, employed for this research work, is implemented using Matlab/Simulink. a detailed comparison between the classic Perturb and Observe P.O algorithm and an other intelligent based on the fuzzy algorithm is conducted to assess MPPT accuracy. The findings demonstrate that the proposed model is characterized by simplicity and the capability to simulate diverse operating conditions.

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I. Introduction

The control of photovoltaic (PV) panels is a critical aspect in optimizing their performance and extracting maximum power output. Efficient control strategies are essential to ensure that the PV panels operate at their maximum power point (MPP), where the energy conversion efficiency is highest. This is particularly important given the variability in environmental conditions, such as changes in solar irradiance and temperature, which can significantly impact the output of PV systems. In this context, various control methods are employed to track and maintain the PV system at its MPP, enhancing overall energy harvesting.

One widely used classic control method for MPPT (Maximum Power Point Tracking) in PV systems is the Perturb and Observe (P&O) algorithm. P&O operates by perturbing the operating point and observing the resulting change in power output to determine the direction towards the MPP. While P&O is simple and commonly employed, it may exhibit oscillations around the MPP and can be sensitive to rapidly changing environmental conditions.

In contrast, intelligent control methods, such as fuzzy logic, have gained attention for their ability to provide more robust and adaptive control in dynamic environments. Fuzzy logic controllers use linguistic variables to represent imprecise information and make decisions based on a set of rules. In the context of PV systems, a fuzzy logic controller can adapt to varying environmental conditions and exhibit a smoother response in tracking the MPP, potentially reducing oscillations and improving overall efficiency.

This comparison between classic control (P&O) and intelligent fuzzy logic underscores the trade-offs between simplicity and adaptability. While classic control methods like P&O are straightforward and easy to implement, intelligent control approaches such as fuzzy logic offer the potential for enhanced performance in complex and dynamic operating conditions. The choice between these control strategies depends on factors such as system complexity, cost considerations, and the specific requirements of the photovoltaic application.

Solar irradiation, site temperature, atmospheric constraints, and intermittency place the photovoltaic system in an unstable and uncertain state, thereby impacting its efficiency and profitability. Introducing an effective control system remains an indispensable recourse to address these challenges. It is through the resolution of this issue that we undertake our current research work.

II. MPPT Control Overview

A successful MPPT-PV system design must take into consideration a few requirements. Stability is the most fundamental design requirement of a dynamic control system. In PV power systems, the switching mode converters are nonlinear systems and the output characteristics of solar array are also nonlinear. Therefore, stability is a critical factor to evaluate a PV MPPT control systems dealing with non-linearity. Besides this, in MPPT control systems, a good dynamic response is desirable for the fast tracking requirement. A good MPPT control algorithm needs to respond quickly to rapidly changing atmospheric conditions like temperature and illumination and track the maximum power points quickly.

MPPT, which stands for Maximum Power Point Tracking, is a crucial aspect of optimizing the performance of photovoltaic (PV) systems. The main goal of MPPT control is to ensure that the PV panels operate at their maximum power point (MPP), where the energy conversion efficiency is highest. This is particularly important given the dynamic nature of environmental conditions, such as changes in solar irradiance and temperature, which can significantly affect the output of PV systems.

MPPT control techniques are employed to continuously adjust the operating point of the PV system, allowing it to track the varying MPP under different conditions. The purpose is to extract the maximum available power from the solar panels at any given moment. Several MPPT algorithms and methods exist, each with its advantages and limitations.

Common MPPT control methods include:

a. ***Perturb and Observe (P&O)**:* This method perturbs the operating point and observes the change in power output to determine the direction towards the MPP. While simple, P&O may exhibit oscillations around the MPP and may not perform optimally in rapidly changing conditions.
b. ***Incremental Conductance (INC)**:* This method uses the incremental conductance of the solar panel to continuously adjust the operating point toward the MPP. It tends to be more accurate than P&O but may be more complex to implement.
c. ***Fuzzy Logic Control**:* Fuzzy logic controllers use linguistic variables to represent imprecise information and make decisions based on a set of rules. In the context of MPPT, fuzzy logic can provide a more adaptive and robust control strategy, particularly in dynamic and uncertain environments.
d. ***Model Predictive Control (MPC)**:* MPC uses a mathematical model of the PV system to predict future behavior and optimize the control actions accordingly. It is effective but may require a more detailed model and computational resources.
e. ***ANN (Artificial Neural Network) Control**:* Artificial Neural Networks are computational models inspired by the structure and functioning of biological neural networks. In the context of MPPT control for photovoltaic systems, ANN control involves the use of neural networks to predict and optimize the operating point of the solar panels.

   - ANNs are trained using historical data to learn the complex relationships between input parameters (e.g., solar irradiance, temperature) and the corresponding optimal operating points.
   - Once trained, the neural network can predict the MPP in real-time based on the current environmental conditions.

f. ***Hybrid Control**:* Hybrid control combines two or more different control strategies to leverage the strengths of each and overcome their individual limitations. In the context of MPPT for photovoltaic systems, hybrid control often involves integrating traditional algorithms with intelligent or learning-based approaches.

   - A hybrid control system might use a fuzzy logic controller as the primary control strategy but switch to a P&O algorithm under certain conditions, combining the adaptability of fuzzy logic with the simplicity of P&O.

g. ***ANFIS (Adaptive Neuro-Fuzzy Inference System) Control**:*

   - ANFIS is a hybrid computational model that integrates fuzzy logic principles with neural network capabilities. In the context of MPPT (Maximum Power Point Tracking) control for photovoltaic systems, ANFIS control combines the adaptability of fuzzy logic systems with the learning capabilities of neural networks.
   - *Fuzzy Logic Base:*
     - ANFIS starts with a set of fuzzy rules based on expert knowledge or historical data.
     - Linguistic variables and membership functions define the fuzzy logic base.

- *Neural Network Layer:*
  - The parameters of the fuzzy logic rules are adjusted using a learning algorithm based on neural network principles.
  - Input-output mappings are learned from training data to enhance the adaptability of the system.
- *Hybrid Learning:*
  - The hybrid nature of ANFIS allows it to adapt to complex and nonlinear relationships in the data.
  - It combines the rule-based reasoning of fuzzy logic with the learning and generalization capabilities of neural networks.
  - ANFIS control is particularly effective in MPPT applications, where it can dynamically adjust the operating point of photovoltaic panels to maximize power output.
  - System Optimization:
    - Beyond MPPT, ANFIS can be applied to optimize other aspects of photovoltaic systems, such as fault detection, energy forecasting, and system monitoring.

In summary, ANFIS control offers a powerful and adaptive approach to MPPT for photovoltaic systems, leveraging the strengths of both fuzzy logic and neural networks to enhance efficiency and performance in varying environmental conditions.

P&O, FLC, ANN, ANFIS and hybrid control represent advanced approaches in the field of MPPT for photovoltaic systems, aiming to improve accuracy, adaptability, and overall efficiency in harnessing solar energy. The choice between these methods depends on factors such as system complexity, available data, and computational resources.

III. Simulation of PV System and Results

The basic layout of the photovoltaic system proposed includes a PV panel, a boost converter, a MPPT controllers and a storage device (Fig. 1).

Although it is known it does not provide the best results in all situations, it is mainly used to test the MPPT controller functionality in the PV system.

The algorithm operates by periodically perturbing the control variable and comparing the instantaneous PV output power after perturbation with that before. Thus, the direction of the next perturbation that should be used is determined [1][2][3][4].

If the change in power $\Delta P > 0$, the direction of the next perturbation keeps the same algebraic sign. That should place the operation point closer to MPP. If $\Delta P < 0$, the algebraic sign of the perturbation should be reversed.

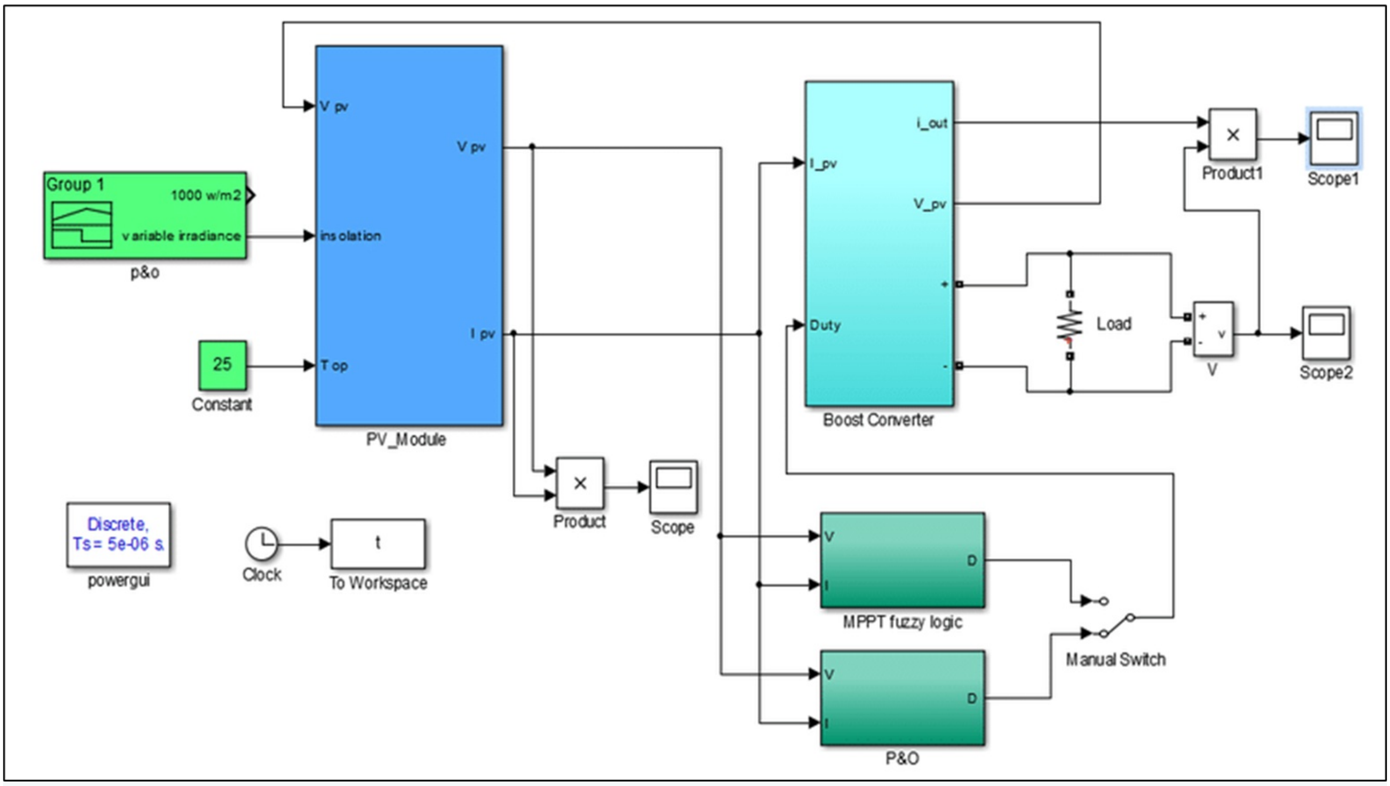

Figure1. Photovoltaic system with fuzzy logic/ P&O control for MPPT.

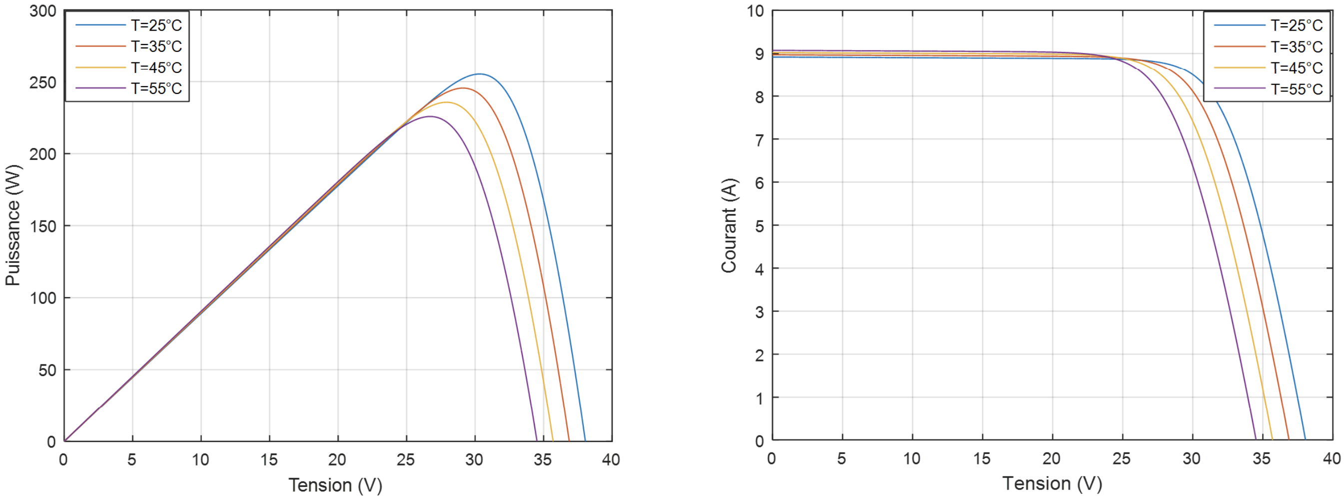

Figure 2. Temperature Influence on the caractéristics Ppv=f (Vpv), Ipv = f (Vpv)

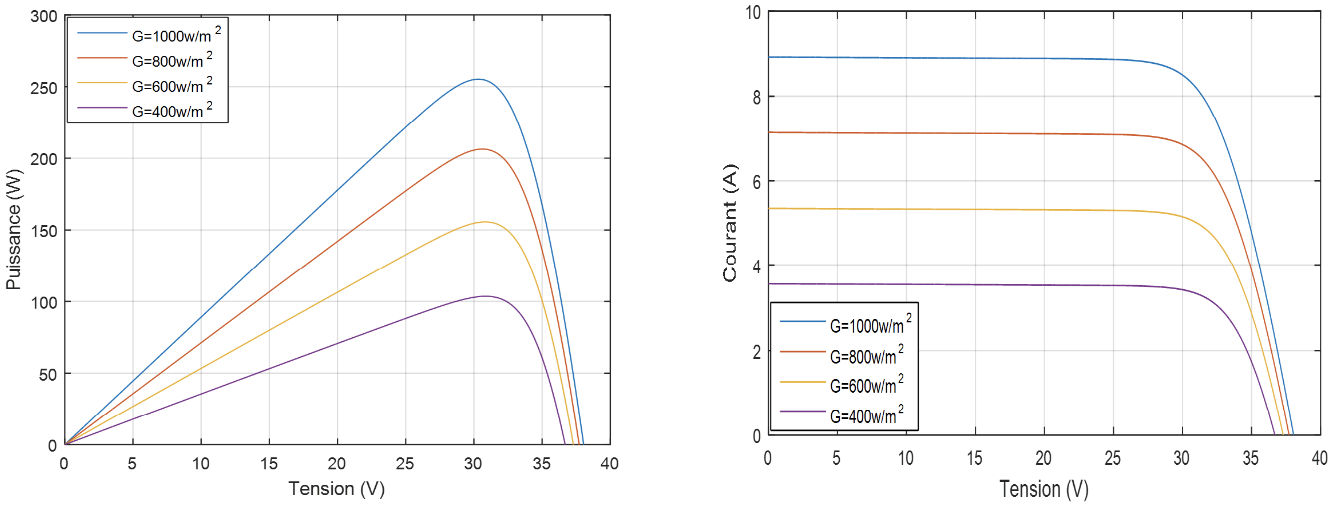

Figure 3. Solar irradiation Influence on the caractéristics du PV Ppv=f (Vpv), Ipv = f (Vpv)

A. *Fuzzy Logic Algorithm*

The second method of tracking the MPP is based on the fuzzy logic. The MPPT controller is generally composed of three main units: the fuzzification, the rule base and the defuzzification (Fig. 2) [5][6].

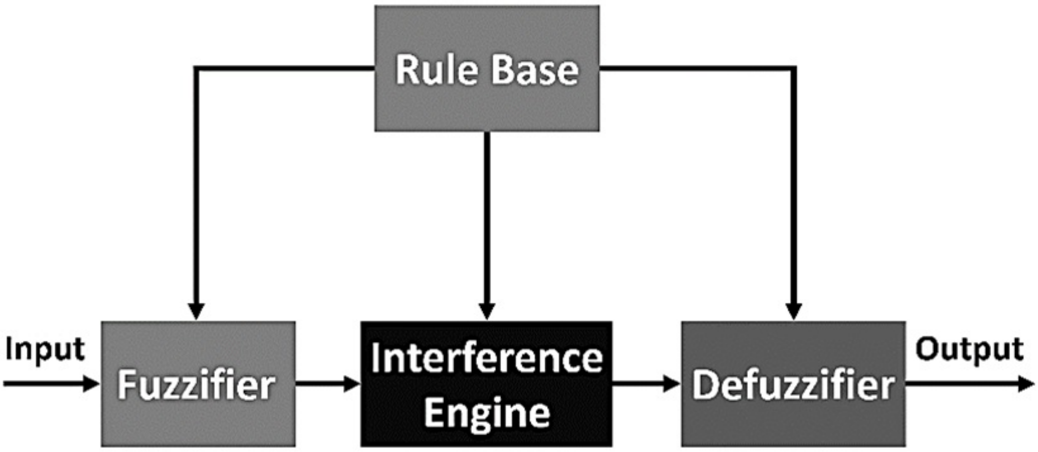

Figure 4. Block scheme of a fuzzy controller.

Fuzzy Logic architecture has four main parts as shown in the diagram:

1. *Rule Base:*
   It contains all the rules and the if-then conditions offered by the experts to control the decision-making system. The recent update in fuzzy theory provides various methods for the design and tuning of fuzzy controllers. This updates significantly reduce the number of the fuzzy set of rules.
2. *Fuzzification:*

   Fuzzification step helps to convert inputs. It allows you to convert, crisp numbers into fuzzy sets. Crisp inputs measured by sensors and passed into the control system for further processing. Like Room temperature, pressure, etc. In our case P and E. P is the power generated by the solar panel and E denotes the error at*k*-th time sample, defined as E(k)=P(k)-P(k-1).

   The inputs P and E are converted to fuzzy membership values on the fuzzy subsets (Figure 3 (a) and (b)). Seven *Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB)*. The E input is coded using three membership functions expressed as linguistic variables denoted*Negative - NEG, Zero - Z, Positive – POZ.* The input variables are fuzzified by using trapezoidal MFs for P and triangular for E.

3. *Inference Engine:*

   The degree of match between fuzzy input and the rules. Based on the % match, it determines which rules need implment according to the given input field. After this, the applied rules are combined to develop the control actions. In our Inference fuzzy rules for the PV system include 13 fuzzy control rules.

   Mamdani fuzzy inference method is used with Max-Min operation fuzzy combination. This method implies the output membership function to be fuzzy sets. After the aggregation process, there is a fuzzy set for every output variable, leading to the necessity of a defuzzification. The operations used in the inference process are: And method is *min*; Or method is *max*; Implication is *min*; Aggregation is *max*.

4. *Defuzzification:*

   At last the Defuzzification process is performed to convert the fuzzy sets into a crisp value. There are many types of techniques available, so you need to select it which is best suited when it is used with an expert system.

   In our case The center of area (COA) algorithm is used for defuzzification of output control parameter Iref. The duty cycle of the boost converter is adjusted thought Iref such that the system operates at the maximum power point.

   The coding of the membership functions for the otput Iref is identical to that of the input P:*Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB)*.

In Table 1 it is summarized the different fuzzy rules used in the fuzzy controller to track the maximum power point.

Tabel 1. Fuzzy rules

P E	NB	NM	NS	Z	PS	PM	PB
NEG	NB	NB	NM	Z	PS	PM	PB
Z	NB	NM	NS	PS	PS	PM	PB
POZ	NM	NM	Z	PS	PS	PB	PB

Every rule of the rule base of the fuzzy logic system establishes a fuzzy relation between the input fuzzy sets and the output fuzzy set Iref. There are 13 rules in the system rule base that make up the control strategy.

The 13 rules are presented to the end-user in *if-then* format like the one below:

- R1: If P is NB and E is NEG then Iref is NB;
- R2: If P is NB and E is Z then Iref is NB;
- R3: If P is NB and E is POZ then Iref is NM; etc.

Figure 3 shows the membership functions of input and output variables. On the ox axis the universe of discourse is represented, while on oy axis there is the membership grade taking values between 0 and 1.

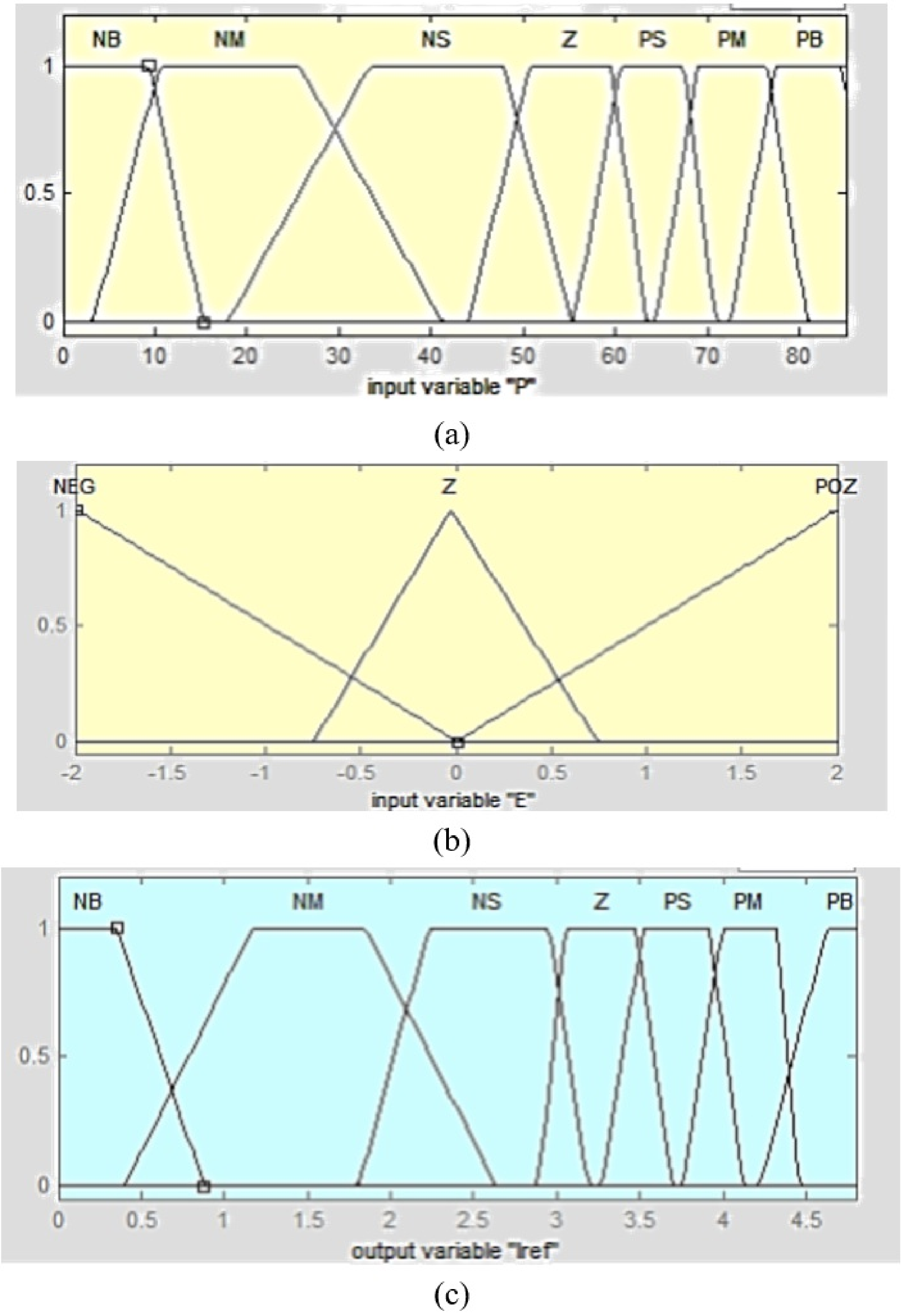

Figure 5. Membership functions for: (a) input P, (b) input E, c) output Iref.

Analyzing the figure 5, are depicts the graphical representation of the algorithm at the core of the controller. Each of the thirteen rows corresponds to a rule. With two inputs and one output, the input-output mapping forms a surface. Figure 6 presents a mesh plot illustrating the relationship between P and E on the input side and the controller output Iref on the output side. This plot results from the rule base comprising the thirteen rules previously outlined. The surface is more or less regular, and the horizontal plateaus are due to flat peaks on the input sets.

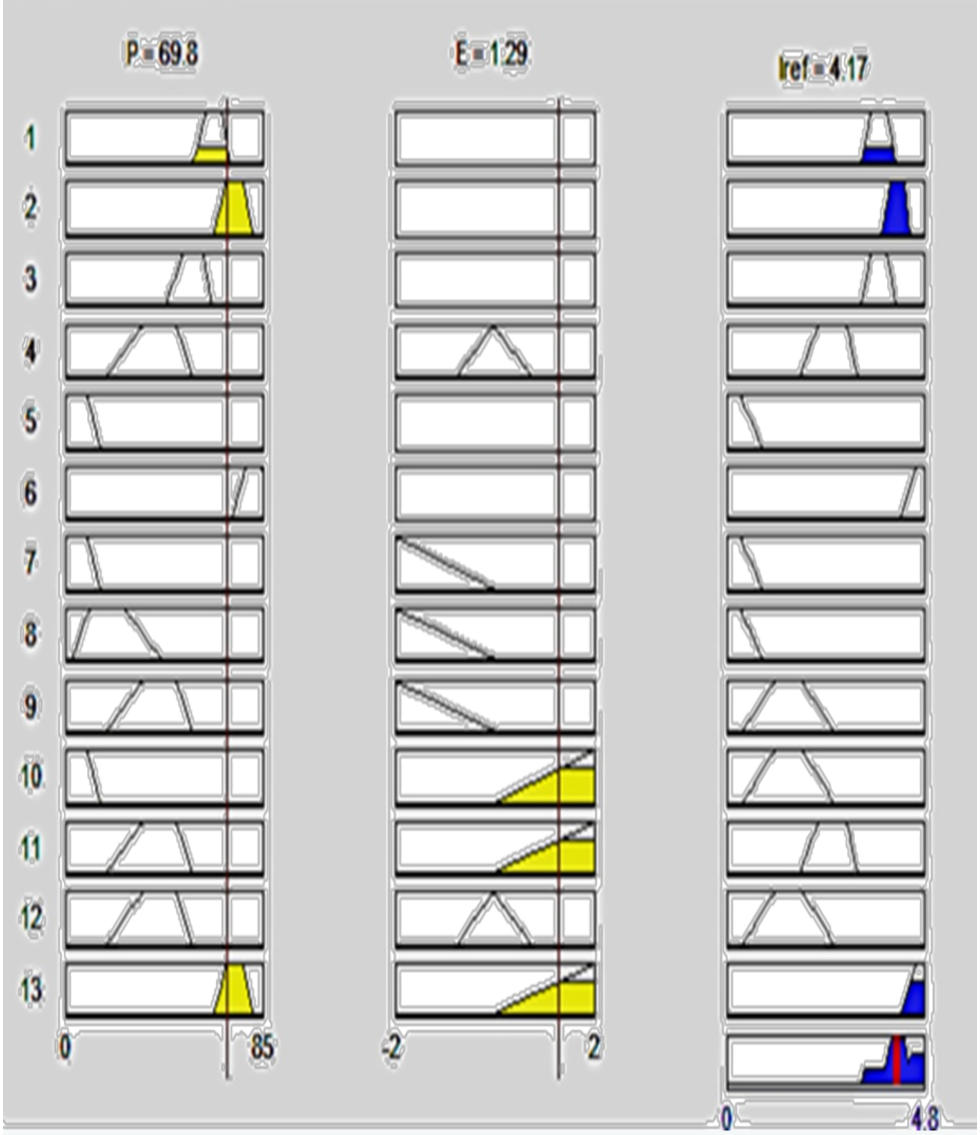

Figure 6. Graphical construction of the control signal in the MPPT controller

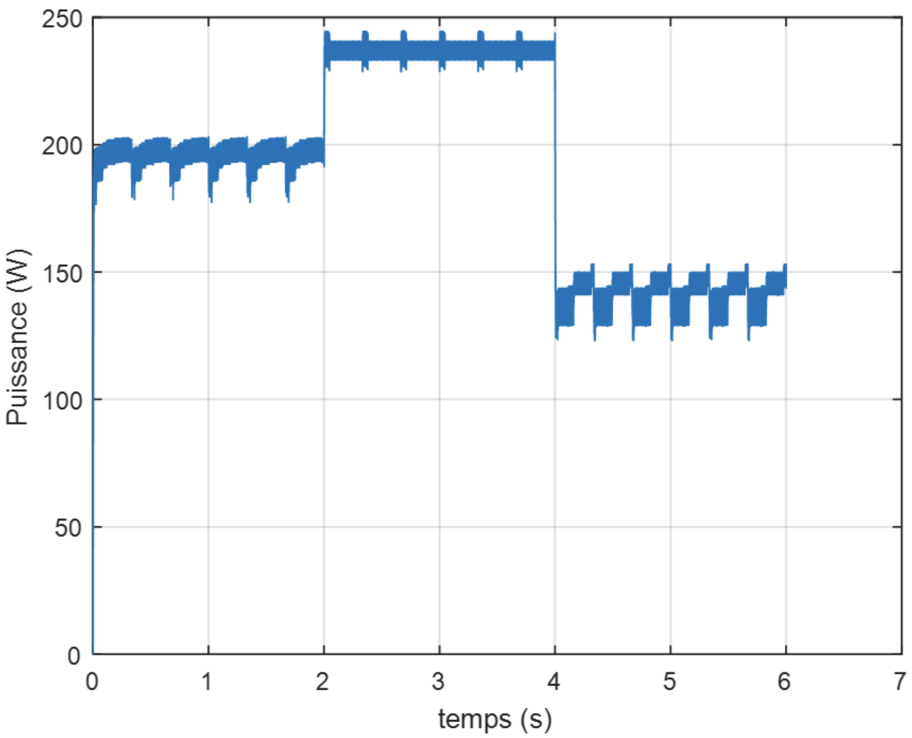

Figure 7. Effect of the MPPT fuzzy control on the PV power

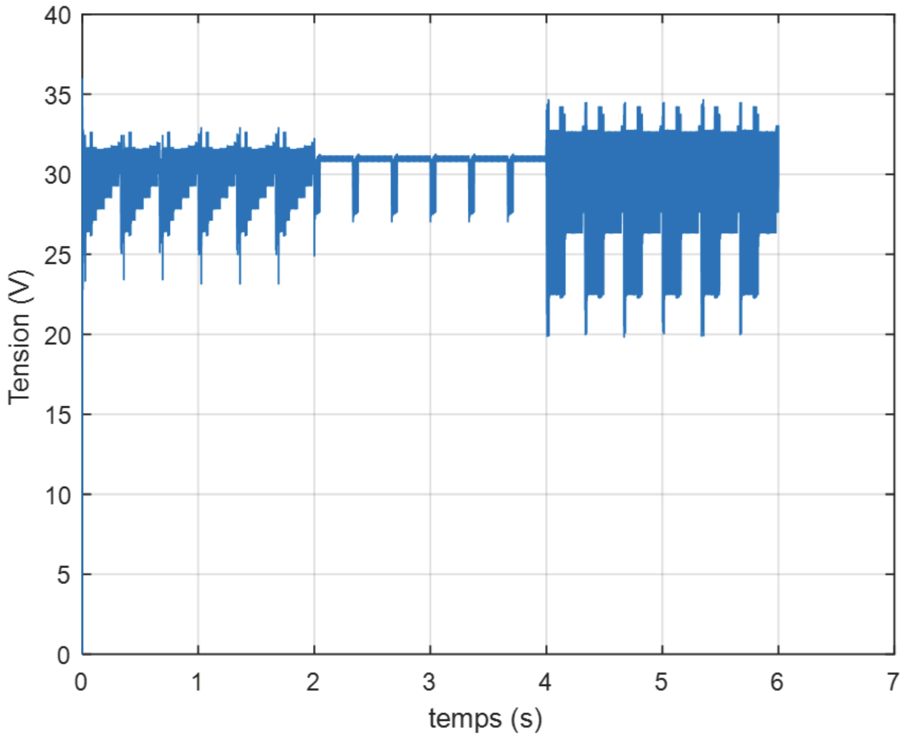

Figure 8. Effev of the MPPT fuzzy control on the PV voltage

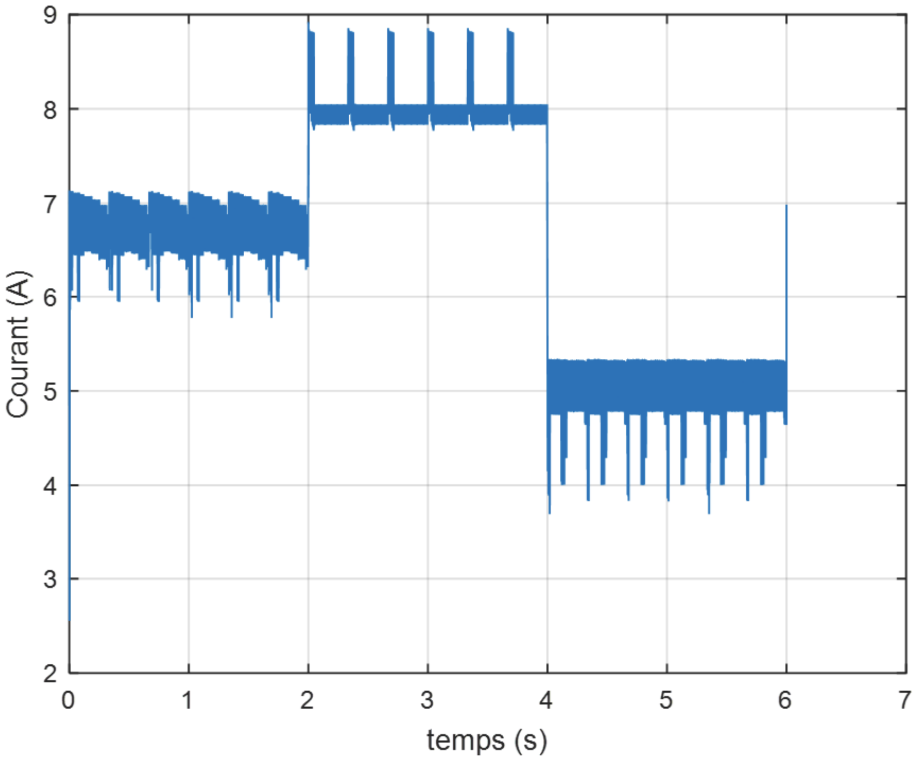

Figure 9. Effect of the MPPT Fuzzy control on the PV current

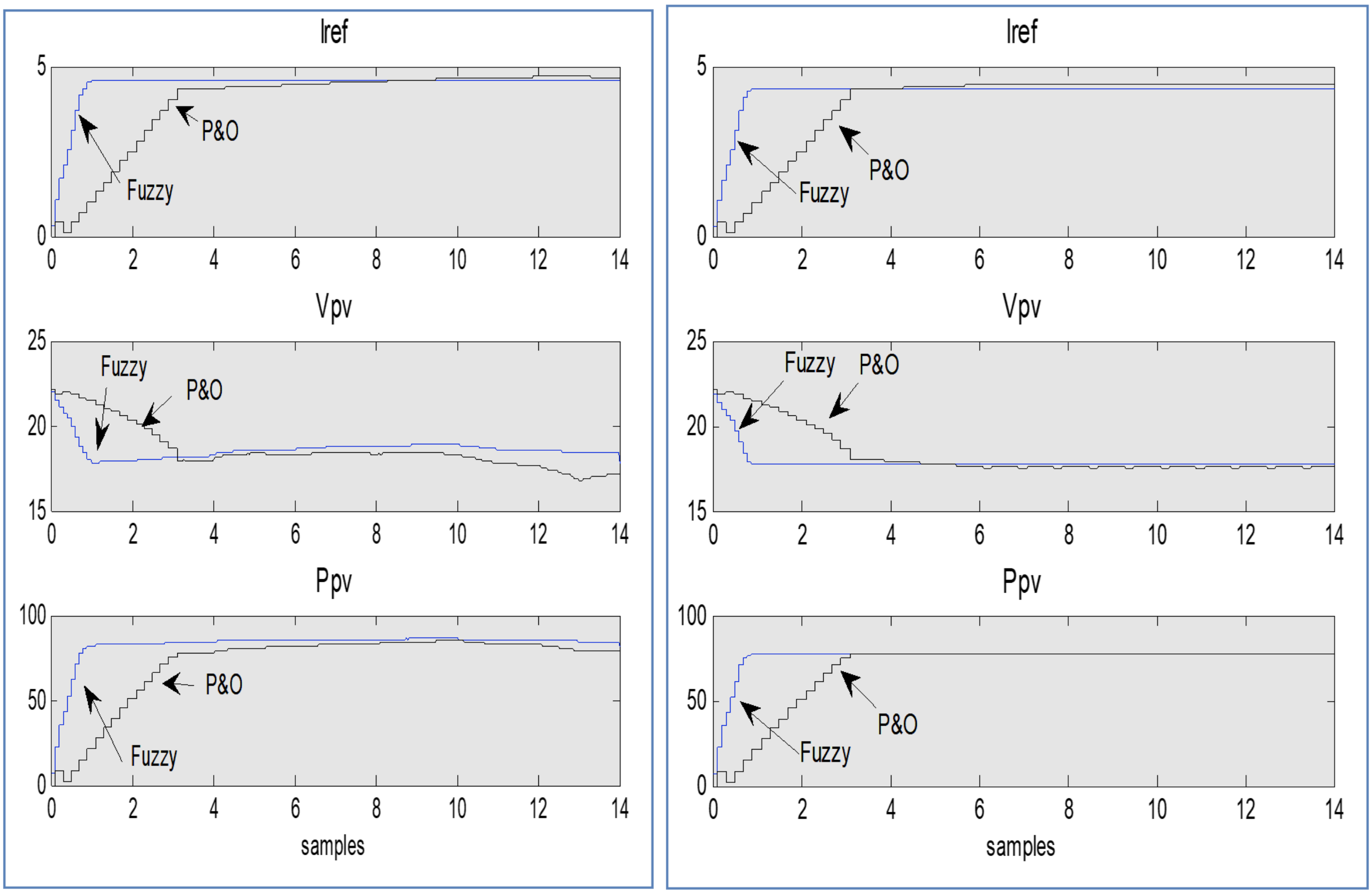

Figure 10. The current, voltage and power of PV panel based on MPPT with P&O and fuzzy control for irradiation variations

Figures 7 to 10 present the simulation results of a solar system implemented in Matlab/Simulink, exploring two MPPT methods: FLC and P&O. The simulations cover two scenarios. The first scenario involves maintaining constant solar irradiation (Figure 10), considering standard conditions with a temperature of 25°C and a solar irradiation level of 1000W/m2. In the second scenario, the system's performance is assessed under varying solar illumination, while keeping the temperature constant. The time response and accuracy of the system in terms of tracking the Maximum Power Point are the targeted outcomes of the solar system simulation. Analyzing them involves highlighting these results as approved values.

IV. Conclusion

In summary, the comparative analysis of two MPPT control techniques, Perturb and Observe (P&O) and Fuzzy Logic Controller (FLC), within the context of photovoltaic systems, underscores the remarkable superiority of FLC. Through a thorough examination of time response and MPPT values under various operational conditions, FLC consistently emerges as the more robust and effective control strategy. Its superior performance implies that Fuzzy Logic Control stands out as a highly promising and reliable approach for optimizing the efficiency and accuracy of photovoltaic systems, offering significant advancements in the pursuit of sustainable and efficient solar energy utilization.

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