Comparative study of the MPPT methods applied to the PV system; Perturbation & Observation technique, sliding mode control and fuzzy logic control

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***Abstract*— The objective of this research paper is to investigate various methods for maximum power point tracking (MPPT) that can be applied to photovoltaic (PV) systems. The study involves the assessment and comparison of three different techniques: perturbation and observation (P&O), sliding mode control (SMC), and fuzzy logic-based MPPT. To transfer the maximum amount of power possible, a DC/DC boost converter is used between the PV system and the load. It has been observed that conventional MPPT approaches such as P&O are unable to detect and track the highest peak, leading to a significant loss of power, so a technique is suggested sliding mode control, which offers many benefits such as durability against parameter changes, minimal current output distortion, and excellent reference tracking. The problem with this technique is high oscillations in the transitional regime. The algorithm based on fuzzy logic control is reliable and effective. The simulation results shown in MATLAB confirm that the fuzzy logic method does operate at the ideal point without oscillations. Moreover, it exhibits good transient behavior and better tracking of the maximum power point.**

Keywords—photovoltaic system, MPPT, P&O, SMC, Fuzzy Logic.

I. Introduction

Every day, the need for electrical energy grows in order to meet the needs of people. As a result of this pressing energy crisis and environmental pollution, the utilization of renewable energy is becoming increasingly important [1][2]. In Algeria, there is enormous potential for solar energy due to its expansive desert regions and high levels of solar radiation. Consequently, the most ideal approach to energy production, according to our research, is through the use of solar energy. [3]. Cells are used in photovoltaic systems to transform solar radiation into electrical energy. When the cells are exposed to light, an electric field is established across the layers, which results in the flow of electricity [4]. The amount of electricity generated is directly proportional to the intensity of the light. Nevertheless, photovoltaic systems face two significant issues due to their inconsistent energy source: (a) low efficiency, and (b) non-linear output characteristics caused by the intermittent nature of solar PV systems, including variations in solar insolation and temperature [5]. To transfer the maximum possible power between a PV system and load, a DC/DC boost converter is utilized along with the MPPT power tracking algorithm [6]. The MPPT algorithm falls into two categories, direct and indirect methods. Direct methods include techniques such as perturbation and observation (P&O), hill climbing (HC), incremental conductance (IC), fuzzy logic (FL), artificial intelligence (AI), and Sliding Mode Control (SMC), which use voltage and current measurements of the PV panel [7]. These direct methods have the advantage of being independent of PV characteristics, temperature, and radiation level during power tracking. Indirect methods, on the other hand, involve curve fitting, look-up table, open circuit voltage, and short circuit current [8]. Indirect methods for maximum power tracking follow a two-step approach, with the initial step being dedicated to optimizing the controller parameters, and the second step utilizing one of the direct MPPT methods to track the power [9].

This work investigates various MPPT control strategies for enhancing the efficiency of photovoltaic systems. One common issue with the P&O MPPT algorithm is the occurrence of oscillations at the MPP due to continuous perturbations and reduced efficiency, making it sensitive to changing atmospheric conditions. To overcome these problems, the researchers suggested using the sliding mode controller (SMC), The approach not only enhances the speed of MPP convergence and ensures stability in the face of load uncertainties and system nonlinearity, but also inherits the sturdy nature of tracking control. However, SMC has a drawback of causing high oscillations in the transitional regime. To address this, the researchers employed fuzzy logic control (FLC), which offers superior transient response tracking and is less sensitive to parametric variation and disturbances. The results show that FLC outperforms MPPT with P&O and MPPT based on SMC, with reduced steady-state fluctuations and better tracking of the maximum power point, resulting in fewer power losses.

II. MODELING OF PHOTOVOLTAIC SYSTEM

Figure 1 displays the equivalent diagram of a genuine photovoltaic cell, which considers the influence of parasitic resistive effects caused by the manufacturing process. This diagram comprises several components, including a diode (d) that characterizes the junction, a current source (Iph) that characterizes the photo-current, a series resistor (Rs) that represents the losses due to the Joule effect, and a shunt resistor (Rsh) that characterizes the leakage current between the upper gate and the rear contact. Typically, the value of Rsh is significantly higher than that of Rs[10].

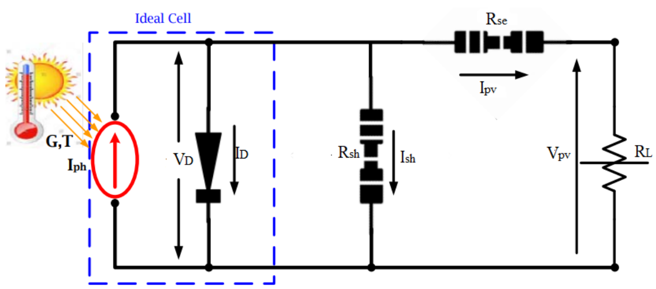

Fig.1. Equivalent circuit of a photovoltaic cell [11].

The equation below provides the output current:

$$I_{PV} = N_{sh} I_{ph} - N_{sh} I_0 \left\{ \exp\left[\frac{q\left(V_{pv} + \frac{N_s}{N_{sh}} I_{pv} R_{se} \right)}{a.k.T.N_s} \right] - 1 \right\} - \frac{V_{pv} + \frac{N_s}{N_{sh}} I_{pv} R_{se}}{\frac{N_s}{N_{sh}} R_{sh}} \quad (1)$$

The relationship between the temperature (T) and the cell reverse saturation current can be expressed as:

$$I_0 = I_{0r} \left(\frac{T}{T_r} \right)^3 \exp\left\{ \frac{qE_G}{k.a} \left[\frac{1}{298} - \frac{1}{T} \right] \right\} \quad (2)$$

The amount of photocurrent Iph is influenced by both the solar radiation (G) and the temperature (T) of the cell[3];

$$I_{ph} = \{ I_{scr} + k_i \ (T\text{-}298) \} \frac{G}{G_r} \quad (3)$$

With

I_{0r}; Reverse saturation current, **I_D**; Current of Diode, k_i; Temperature coefficient of short-circuit current, **I_{scr}**; Current generated by the light at nominal condition, **k**; Constant of Boltzmann (1.38.10-23J / K), **q**; The electron's charge (1.6.10-19C), **a**; p-n junction ideality factor, **E_G**; Band gab and **G, G_r;** Real and reference solar radiation.

III. PERTURBATION AND OBSERVATION TECHNIQUE(P&O)

The perturbation and Observation (P&O) algorithm are the most used in the literature, especially in practice because of its ease of implementation. This method is based on performing a perturbation (increase or decrease) on the value of the output voltage or current of the system and comparing the output power of the system after the perturbation with the power of the system before the perturbation. When it changes the system voltage and its ability to increase (i.e.: $(((\Delta P\_pv) / (\Delta V\_pv)) > 0)$, the control system will move the action point in the same direction (i.e., it makes a perturbation increasing), and in the case of $(((\Delta P\_pv) / (\Delta V\_pv)) < 0)$ the system will move the work point in the opposite direction (i.e., it makes a perturbation decreasing). In the next perturbation, the system proceeds in the same manner. Figure 2. shows the variation of the duty ratio or voltage depending on the power. [12,13]

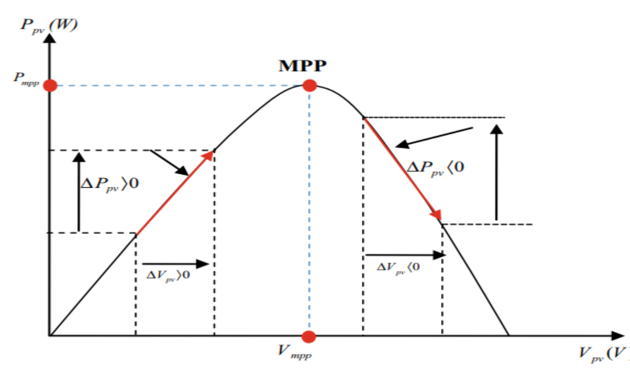

Fig.2. Functional characteristics of the P&O method.

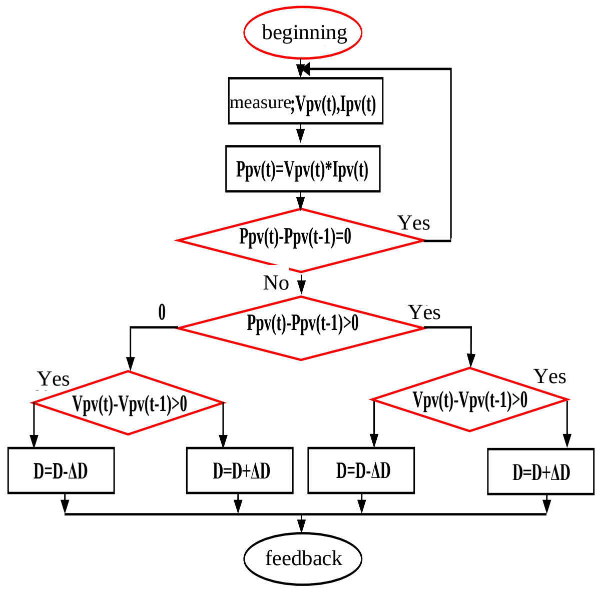

Fig.3. Flowchart of the P&O MPPT algorithm.

IV. SLIDING MODE CONTROL

Sliding mode control pertains to a distinct mode of operation utilized for systems that have variable structures. This approach involves directing the system's state path towards the sliding surface and then intermittently adjusting it to reach the equilibrium point through appropriate switching logic, as shown in Figure 4. On the surface, the dynamics of the system is independent of that of the initial process, ensuring stability and robustness to large variations in system parameters [14].

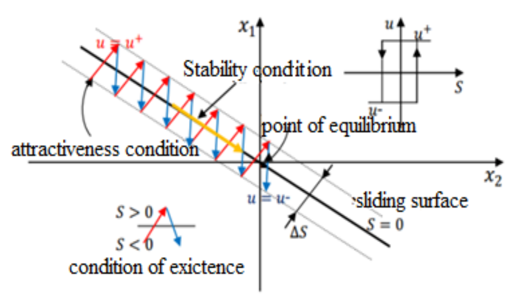

Figure 4. Principle of the sliding mode control.

The design of the control law can be summarized in three steps;

A. Selection of the sliding surface

The sliding surfaces are selected based on a general equation, which can be expressed as follows;

$$S(X)=\left(\frac{d}{dt}+\lambda\right)^{r-1}\left(X^{d}-X\right) \quad (3)$$

With

λ: is a positive constant.

r: is the relative degree, equal to the number of times the output must be derived to bring up the control.
(Xd-X): the tracking error.

Where X: state variable of the control signal and Xd : is the desired signal.

B. The convergence conditions:

The Lyapunov equation defines the convergence condition, resulting in an attractive and unchanging surface;

$$S(X)\dot{S}(X)\leq 0 \quad (4)$$

C. Determination of the control law:

The calculation of the control signal is represented by the following equation:

$$U=U_{eq}+U_{n} \quad (5)$$

The term "Ueq" refers to the control that is equivalent, while the term "Un" pertains to the control that involves switching. [15,16]

V. MPPT CONTROL BY SLIDING MODE OF PHOTOVOLTAIC SYSTEM

A. Selection of the sliding surface:

$$S(X)=\frac{dP_{pv}}{dV_{pv}}=I_{pv}+\frac{dI_{pv}}{dV_{pv}}V_{pv}=N_{sh}I_{sc}-\left(N_{sh}I_{sc}+\frac{N_{sh}I_{sc}}{a.k.T.N_{s}}\right)\exp\left(\frac{V_{pv}-N_{s}V_{co}}{a.k.T.N_{s}}\right) \quad (6)$$

B. The convergence conditions:

$$S(X)=\frac{dS}{dx_{1}}.\dot{x}_{1}=0 \quad (7)$$

C. Determination of the control law[17]:

$$U=\frac{I_{pv}}{I_{L}}-K.sign\left(I_{pv}+\frac{dI_{pv}}{dV_{pv}}V_{pv}\right) \quad (8)$$

VI. FUZZY LOGIC CONTROL

The use of this technique, first described by Lotfi Zadeh (1965), has become a viable alternative to several control systems in recent decades. Fuzzy logic techniques are now used in practically every sector and may be used to operate wind turbines with nonlinear models. The fuzzy logic structure is divided into three sub-blocks, as illustrated in Figure 5, fuzzification, inference, and defuzzification [18][19].

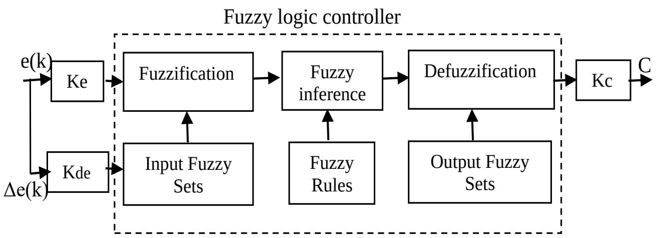

Fig. 5. Structure of the FLC.

D. Fuzzification

During this stage, the numerical input variables (e(k) and Δe(k)) are transformed into linguistic variables based on a membership function. This process involves the use of seven levels of fuzziness, which are represented by ZE (Zero), PB (Positive Big), PM (Positive Mean), PS (Positive Small), NB (Negative Big), NM (Negative Mean), and NS (Negative Small) [20]. These levels are depicted in Figure 6.

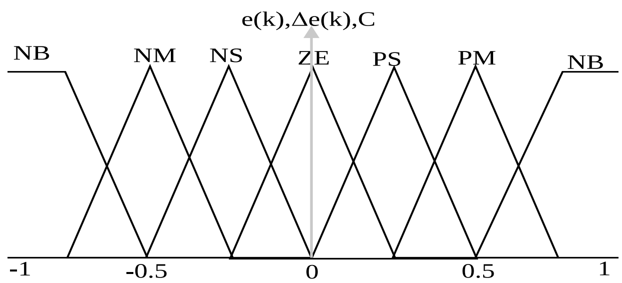

Fig.6. Membership functions for variables linguistics of the FLC.

E. Fuzzy Rule Base

The table below gives 49 inference rules of different combinations between the variables linguistics e(k), Δe(k) with the output C to get the required reference signals [20]. The IF-THEN rules of the following types indicate the fuzzy mapping of the input variables to the output variable:

IF [e(k) is NB] and [Δe(k) is NB] THEN [C is PB]
IF [e(k) is PB] and [Δe(k) is PB] THEN [C is NB]

TABLE I. Fuzzy Rule Table For FLC

e(k) Δe(k)	NB	NS	ZE	PS	PB
NB	ZE	ZE	NS	PS	PB
NS	ZE	ZE	ZE	PS	PB
ZE	NB	NS	ZE	PS	PB
PS	NB	NS	ZE	ZE	ZE
PB	NB	NS	PS	ZE	ZE

F. Inference and Defuzzification

This approach transforms the inferred fuzzy control action to a numerical variable at the output using the eq (9) by constructing the union of the outputs of each rule.[21]

$$\overline{M_n} = \frac{\overline{\sum_{i=1}^{N} \mu_i C_i}}{\sum_{i=1}^{N} \mu_i} \quad (9)$$

Where;
N: number of rules.
μ_i: designates the membership rank.
C_i: the coordinate linked to the respective output.

In our MPPT controller (FLC), we use PV voltage and PV current as subsystem inputs for generation error (e) and error change. The output is the duty cycle D of the first boost converter.

VII. SIMULATION RESULT

The photovoltaic module (SunPower SPR-400E WHT-D) is chosen for modelling and then simulation. It contains 54 monocrystalline silicon solar cells, and provides a rated maximum power of 21.6 KW. The characteristics of the PV system are shown in table 2:

TABLE II. PHOTOVOLTAIC PV SYSTEM PROPOSED PARAMETERS.

Solar panel model	**Value**
Solar panel wattage	400.22W
Voc	85.3V
Vmpp	72.9V
Icc	5.87A
Impp	5.49A
Ns, Np	9 in series, 6 in parallel
Boost converter inductance	0.5063 mH
Filter capacitance	2192 µF
switching frequency for DC/DC converter	5 KHZ
Total power of system at MPP	400.22*9*6 =21.6KW

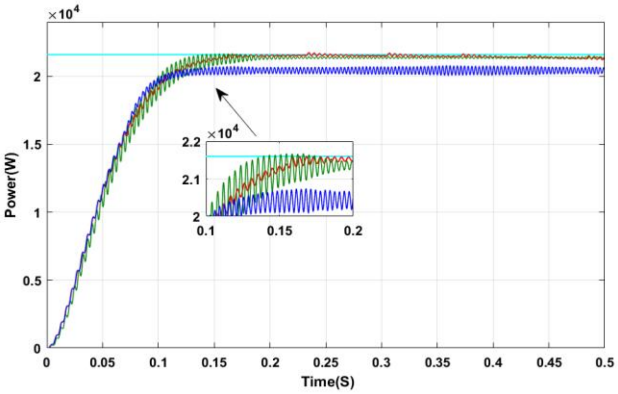

Fig.7. PV system power response for different MPPT controllers.

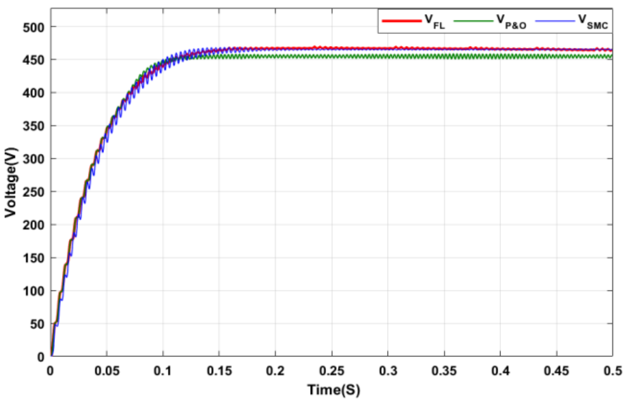

Fig.8. PV system voltage response for different MPPT controllers.

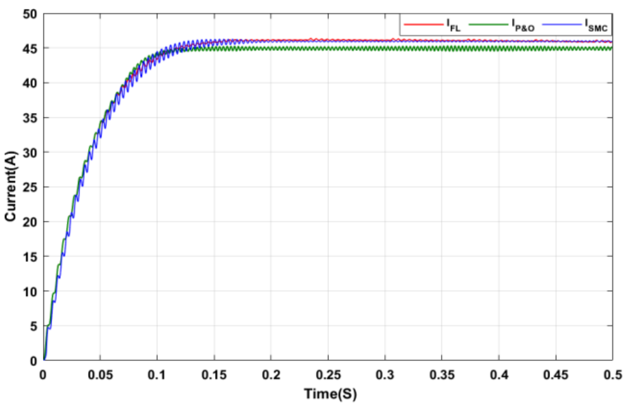

Fig.9. PV system current response for different MPPT controllers.

In this section, the solar system is first evaluated by simulation with the simulation tool MATLAB/Simulink. Then, the three MPPT tracking methods are studied: the P&O method, the method using the sliding mode controller, and the fuzzy logic method. Simulations were conducted on both systems using standard conditions, with temperature set to T = 25°C and solar irradiance set to irr = 1000 W/m. The aim of these simulations was to observe the deviation of the operating point from the MPP point and assess the losses incurred due to fluctuations around this point. Results indicate that the P&O algorithm is highly reliant on initial conditions and causes oscillations around the optimal value. The primary drawback of this algorithm is its tendency to produce high errors between output power and reference power, in addition to generating strong oscillations. For the sliding mode controller, it can be seen that it works well compared to the MPPT with P&O. SMC allows for faster response to P&O, reduced steady-state fluctuations, and better tracking of the maximum power point with less power loss. The problem with this technique is high oscillations in the transitional regime. The algorithm based on fuzzy logic control is a reliable and effective algorithm. This method really does operate at the ideal point without oscillations. Moreover, it exhibits good transient behavior and better tracking of the maximum power point. The implementation of this kind of algorithm is more difficult than the implementation of conventional algorithms.

The following table summarizes the comparison between the MPPT with P&O control, MPPT with SMC and MPPT based on FL control applied to the system PV:

TABLE III. Comparison Between MPPT With P&O And FLC.

Control	P&O	SMC	FLC
Vmax	455V	465V	465V
-Oscillation permanent regime. -Oscillation transient regime.	0.5 0.5	0.15 0.8	0.05 0.05
Pmax	20.4W	21.4W	21.5W

VIII. CONCLUSION

In this work, different MPPT control strategies are studied and developed for photovoltaic systems to improve their efficiency. According to the simulation findings, while the SMC algorithm outperforms P&O, the fuzzy logic-based control displays favorable behavior and superior performance in terms of maximum point tracking and steady-state oscillation when compared to other methods, where the power losses are lower in the transient regime and the steady-state; this implies an improvement of the system's efficiency.

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