http://doi.org/10.35784/iapgos.6152

received: 26.04.2024 | revised: 25.11.2024 | accepted: 02.12.2024 | available online: 21.12.2024

PV SYSTEM MPPT CONTROL: A COMPARATIVE ANALYSIS OF P&O, INCCOND, SMC AND FLC ALGORITHMS

Khoukha Bouguerra[1], Samia Latreche[1], Hamza Khemliche[2], Mabrouk Khemliche[1]

[1] Ferhat Abbas Sétif 1 University-UFAS, Electrical Engineering Department, Automatic Laboratory of Sétif-LAS, Sétif, Algeria, [2]Research Centre in Industrial Technologies, Algiers, Algeria

Abstract. *The importance of solar energy is manifested in the growing demand for renewable energy sources around the world, which is fueled by environmental concern and the scarcity of conventional energy. Maximum power point trackers (MPPTS) are necessary in solar energy systems due to atmospheric changes that threaten the efficiency of solar energy systems. This article compares MPPT technologies. Including traditional and modern techniques, and despite the results achieved by classical techniques in maximizing and extracting as much energy as possible, they face a big problem in reaching the bone energy point. These provide modern technologies such as FLC and SMC. They provide exceptional accuracy and excellent response in all environmental conditions but come with additional complexity and higher cost. These technologies are ideal in applications that require high performance under continuously changing conditions or in difficult environments (such as large solar power systems or systems dealing with large fluctuations in illumination). This research aims to conduct a comprehensive study and compare of classical technologies (P&O and IncCond) and modern technologies sliding mode control (SMC, Fuzzy Logic Control – FLC), taking into account factors such as efficiency, complexity and response time. Tests were conducted under different climatic conditions to understand and enhance the efficiency of MPPT technologies. Our study highlights the enhanced performance for methods based on modern technologies. This study provides a comprehensive comparative analysis, and by improving the efficiency and reliability of solar energy systems, our research supports the advancement of sustainable energy solutions.*

Keywords: PV, DC/DC converter, MPPT techniques, fuzzy logic control, sliding mode control

STEROWANIE MPPT SYSTEMU PV: ANALIZA PORÓWNAWCZA ALGORYTMÓW P&O, INCCOND, SMC I FLC

Streszczenie: *Znaczenie energii słonecznej przejawia się w rosnącym zapotrzebowaniu na odnawialne źródła energii na całym świecie, które jest napędzane troską o środowisko i niedoborem energii konwencjonalnej. Trackery punktu maksymalnej mocy (MPPTS) są niezbędne w systemach energii słonecznej ze względu na zmiany atmosferyczne, które zagrażają wydajności systemów energii słonecznej. Niniejszy artykuł porównuje technologie MPPT. Pomimo wyników osiąganych przez klasyczne techniki w maksymalizacji i wydobywaniu jak największej ilości energii, napotykają one duży problem w osiągnięciu punktu energetycznego. Zapewniają to nowoczesne technologie, takie jak FLC i SMC. Zapewniają one wyjątkową dokładność i doskonałą reakcję we wszystkich warunkach środowiskowych, ale wiążą się z dodatkową złożonością i wyższymi kosztami. Technologie te są idealne w zastosowaniach wymagających wysokiej wydajności w stale zmieniających się warunkach lub w trudnych środowiskach (takich jak duże systemy energii słonecznej lub systemy radzące sobie z dużymi wahaniami oświetlenia). Niniejsze opracowanie ma na celu przeprowadzenie kompleksowych badań i porównanie klasycznych technologii (P&O i IncCond) oraz nowoczesnych technologii sterowania ślizgowego (SMC, Fuzzy Logic Control – FLC), biorąc pod uwagę czynniki takie jak wydajność, złożoność i czas reakcji. Testy przeprowadzono w różnych warunkach klimatycznych, aby zrozumieć i zwiększyć wydajność technologii MPPT. Nasze badanie podkreśla zwiększoną wydajność metod opartych na nowoczesnych technologiach. Opracowanie to zapewnia kompleksową analizę porównawczą, a poprzez poprawę wydajności i niezawodności systemów energii słonecznej, nasze badania wspierają rozwój zrównoważonych rozwiązań energetycznych.*

Słowa kluczowe: PV, konwerter DC/DC, techniki MPPT, sterowanie logiką rozmytą, sterowanie ślizgowe

Introduction

One of the biggest problems facing humanity is climate change, which poses a significant threat to the ecosystem and life on Earth. This climate change, which is reflected in rising temperatures and increased frequency of natural disasters, is a direct result of human activity, specifically greenhouse gas emissions resulting from the burning of fossil fuels.

With the increasing global demand for energy, the available reserves of these resources have begun to deplete faster than expected, which is why the world is turning towards more sustainable alternatives. Renewable energy technologies stand out as an effective solution to these problems.

These technologies contribute to reducing carbon emissions and providing sustainable and renewable energy sources, such as solar, wind, and hydroelectric power.

The transition to renewable energy represents a profound shift in thinking and energy production worldwide, and it is considered a crucial step towards achieving sustainable development goals. These sources are seen as innovative and safe solutions, and they have become more efficient and less costly than ever before.

The opportunities provided by this energy in terms of sustainable advancement, environmental preservation, and enhancing energy independence make it the most logical choice for the future. With more research and development, renewable energy is expected to become the dominant global choice in the near future, contributing to construction a more sustainable and safer world for future generations.

MPPT algorithms are crucial; especially in the face of changing environmental conditions. photovoltaic system needs continuous tracking of this point to ensure maximum energy extraction. So, when the voltage and current of the solar panels are at their peak potential, the energy production in the photovoltaic system reaches the maximum power point (MPP), allowing for the extraction of the maximum amount of energy from the panels.

In order to achieve this successfully, MPPT (Maximum Power Point Tracking) algorithms must be used to ensure the system operates continuously at this optimal position. And by changing the voltage

Maximum Power Point Tracking (MPPT) techniques in photovoltaic systems are divided into several types based on their method of controlling the voltage of solar panels and their interaction with environmental conditions.

Traditional MPPT algorithms include the Perturb and Observe (P&O) algorithm, which uses periodic voltage changes to monitor energy changes, P&O is a simple and effective method in many cases, but it can suffer from oscillation around the maximum power point.. Incremental Conductance Algorithm (INC) is more accurate but requires more complex computation.

Advanced MPPT algorithms like Sliding Mode Control (SMC) Sliding Mode Control is a type of control characterized by high flexibility and the ability to handle disturbances and nonlinearity in systems. It is used in controlling systems characterized by sudden or nonlinear changes, such as solar electrical systemsand Fuzzy Logic Control (FLC) offer high tracking precision but require high computational capabilities.

The Article aims to design and implement four MPPT controllers using Matlab/Simulink, evaluate their effectiveness in varying radiation and temperature conditions, compare different controllers for efficiency in solar energy harvesting, and provide analytical guidance.

Our goal is to provide professionals, researchers and engineers with the knowledge and resources they need to choose and use MPPT algorithms.

In addition, by using Matlab/Simulink to evaluate these controllers within the actual controllers, we hope to provide more useful and realistic insights into their performance. The ultimate goal of our study is to develop solar energy systems and control algorithms, which will lead to a more efficient and sustainable energy future. The paper is organized into 6 sections: the first addresses problems, objectives, and the importance of the study. In the second section, the mathematical model is reviewed and the characteristics of the school system are analyzed. The third section covers traditional techniques with a presentation of simulations and analysis of results. Sections 4 and 5 present modern technologies and the results obtained, along with an analysis comparing old and new technologies. In Section 6, conclusions and recommendations are made based on the results reached.

1. PV system modelling and simulation

1.1. PV system description

The photovoltaic generating system comprises a photovoltaic generator, a DC-DC converter, a digital controller, and a load.

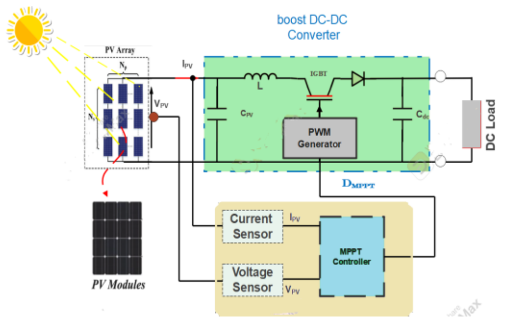


Fig. 1. Simple PV system block diagram MPPT

1.2. PVG modeling

The modelling of the PV generator is given from Fig. 2 and represented by the following equations.

The general mathematical equation for a PV cell is as follows:

$$I = I_{ph} N_p - I_d - I_{sh} \tag{1}$$

I_{ph} is a stream of light. The diode's current is called the I_d, while the shunt current is called the I_{sh}. The following is the equation for photovoltaic current.

$$I_{ph} = I_{sc} + K_i.(T - 298)\frac{G}{1000} \tag{2}$$

The conversion current equation is given as follows:

$$I_{sh} = \frac{V_{pv} + I_{pv} R_s}{R_{sh}} \tag{3}$$

The dark current equation is as follows

$$I_d = I_s \left[\exp\left(q \frac{V_{pv} + R_s I_{pv}}{N_S V_t} \right) - 1 \right] \tag{4}$$

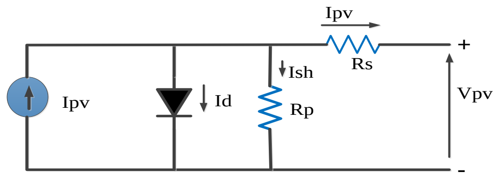


Fig. 2. PV cell

The following equation describes how the reserved saturation current changes with temperature:

$$I_0 = I_{rs} \left(\frac{T}{T_n} \right)^3 \exp \left[\frac{qE_{g0} \left(\frac{1}{T_n} - \frac{1}{T} \right)}{nK} \right] \tag{5}$$

In another, the output current dependence is given as follows

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q(V + IR_S)}{nKN_s T} \right) - 1 \right] - I_{sh} \tag{6}$$

where V_{oc} represents the cell voltage, R_s stands for the resistance series cell, R_p for the parallel resistance, and V_t for the module's thermal voltage: V_t is equal to $N_s\ KT/q$. The number of cells connected in series is denoted by N_s, and the number connected in parallel by N_p. T is the cell's temperature; q is the electron charge, which is equal to $1.6{\cdot}10^{-19}$ C; K is the Boltzmann constant, which is equal to $1.3854{\cdot}10^{-23}$ J/K; and $n = 1.3$ is the diode's ideality factor.

1.3. Simulation study

In order to understand the influence of environmental factors (such as temperature and solar radiation), dust accumulation, tilt angle direction, misdirection effect and internal factors, we conducted simulations using MATLAB/Simulink as shown in Fig. 3 and the results are presented in Fig. 4–7 in different conditions of temperature, radiation and change in the rectifiers of the photovoltaic panel characteristics used in the creation of the PV mathematical model with:

$$N_s = 36;\ G_{ref} = 1000\ W/m^2;\ T_{ref} = 25°C;\ P_{mp} = 40\ W$$

$$V_{mp} = 18.24\ V; I_{mp} = 2.20\ A;\ V_{oc} = 21.8\ V;\ I_{sc} = 2.35\ A$$

Case 1: Irradiance effect

Fig. 4 shows the properties of an electric cell under a variation in irradiance of several values (1200, 1000, 800, 600, 400 W/m²) while the temperature is maintained at 25°C. Little voltage changes and the power increases when the irradiance increase.

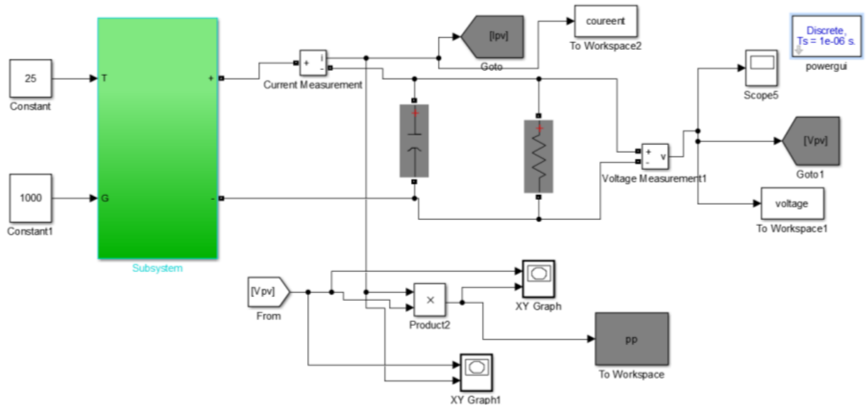


Fig. 3. Simulation model of PV system

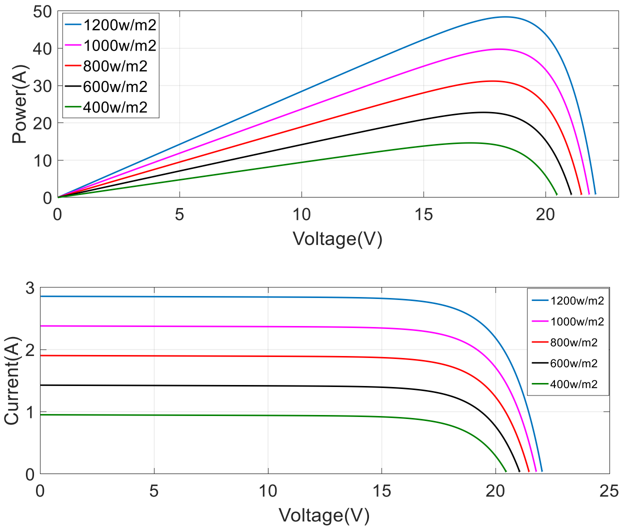


Fig. 4: P-V and I-V characteristics of the solar panel

Table 1. Photovoltaic cell performance for different Irradiance intensity

Irradiance (W/m²)	400	600	800	1000	1200
Pmpp (W)	14.672	23	31.2	40	48.5
Voc (V)	20.46	21.463	21.514	21.28	22.041
Isc (A)	0.954	1.431	1.912	2.35	2.85

Case 2: Temperature effect

In order to understand the characteristics of the photovoltaic cell we made a temperature change (0, 15, 25, 35, 45°C) and irradiance stabilization at 1000 W/m². Where we observe an array increase in current at higher temperature and a decrease in voltage due to an increase in I_{sc} and as a result the resulting energy decreases

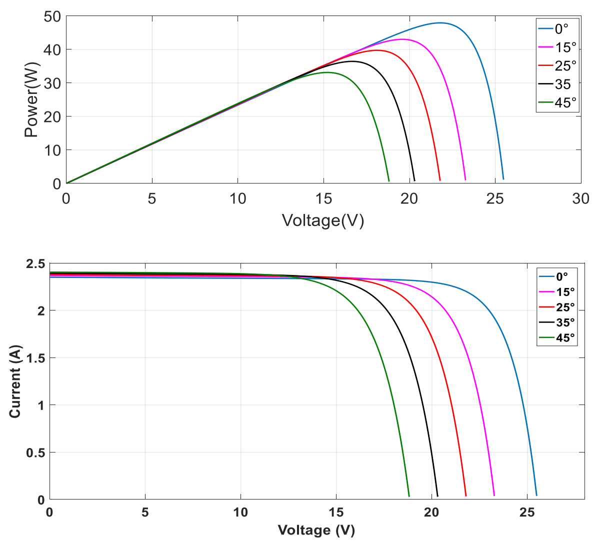


Fig. 5. Solar panel's P-V and I-V characteristics with a irradiance of G = 1000 W/m²

Table 2. Performance of a photovoltaic cell under alternating temperature

Temperature (°C)	0	15	25	35	45
Pmpp (W)	48	43	40	36.5	33.2
Voc (V)	25.5	23.26	21.8	20.3	18.8
Isc (A)	2.38	2.365	2.35	2.046	2.03

Case 3: Series resistance variation

Fig. 6 shows the effect of series resistance (0, 2, 0.5, 0.9, 2 Ω), where the effect of resistance on the output power is shown with a diaper on the same current and voltage. Its effect in the slope of the curve is very obvious.

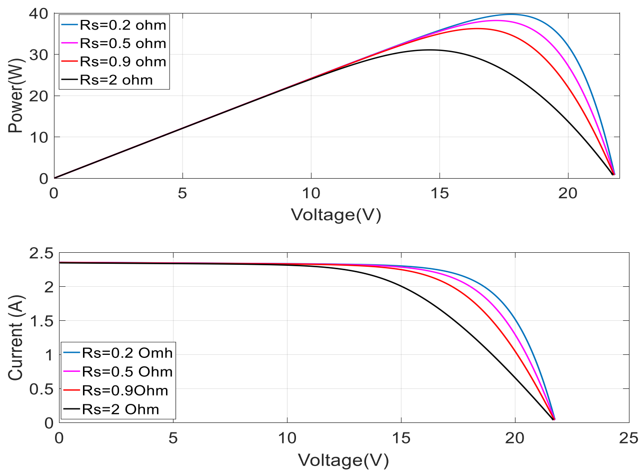


Fig. 6. P-V and I-V characteristics under series resistance variation

Table 3. The outcomes of PV modules with different series resistance

Series Resistance (Ω)	0.2	0.5	0.9	2
Pmpp (W)	40	38	36.75	31.09
Voc (V)	21.28	21.2612	21.245	21.2031
Isc (A)	2.4295	2.4287	2.4277	2.425

Case 4: Shunt resistance variation

The following graphs illustrate the impact of shunt resistance fluctuation on the photoelectric property for various values (5, 8, 15). Power loss is caused by low shunt resistors (5, 8, 15 Ω), which also lowers the values of I_{SC} and V_{OC}.

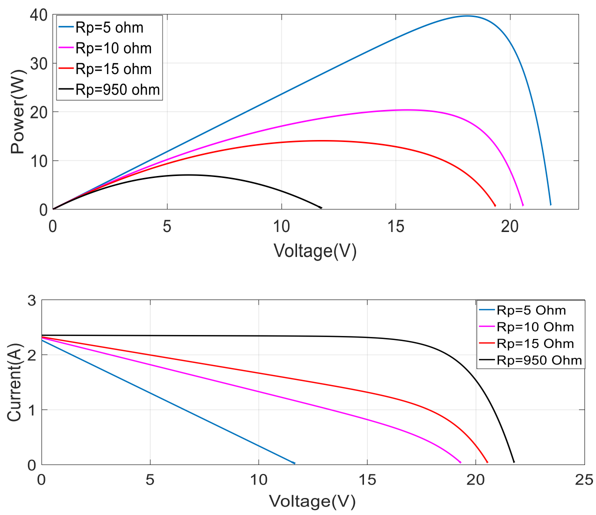


Fig. 7. P-V and I-V characteristics under series resistance variation

Table 4. PV Module results for varying series resistance

Shunt Resistance (Ω)	5	10	15	950
Pmpp (W)	7.75	14.5	20.567	40
Voc (V)	11.75	19.375	20.567	21.28
Isc (A)	2.2105	2.245	2.298	2.35

2. Power conversion structure

A boost converter is necessary for photovoltaic systems. To keep the maximum output power constant, it employs an MPPT controller. Fig. 8 Boost converter diagram.

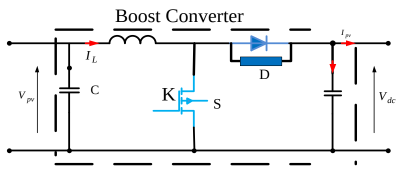


Fig. 8. DC-DC boost converter scheme

$$V_{pv} = L\frac{dI_L}{dt} + V_{dc}\left(1-K\right)$$
$$\left(1-K\right)I_L = C\frac{dV_{dc}}{dt} + I_{pv} \quad (7)$$

The step-up chopper's gain is directly correlated with the duty cycle

$$\frac{V_{dc}}{V_{pv}} = \frac{1}{1-K} \quad (8)$$

In the continuous mode of the DC-DC boost converter, the state space average model is depicted by

$$\begin{cases} \dfrac{dI_{pv}}{dt} = \dfrac{V_{pv}}{L} - \dfrac{V_{dc}}{L}\left(1-K\right) \\ \dfrac{dV_{dc}}{dt} = \dfrac{-V_{dc}}{RC} + \dfrac{I_{pv}}{C}\left(1-K\right) \end{cases} \quad (9)$$

$$\dot{x} = f(x,t) + g(x,t)u(t) \quad (10)$$

$$X = \left[I_{pv}V_{dc}\right]^T \ and\ K \in \left[0,1\right] \quad (11)$$

3. MPPT methods

We will examine the structure, modelling, and operation of the photovoltaic solar power system in conjunction with the MPPT controller in this section. The two main types of photovoltaic solar energy systems are grid-connected and off-grid. For this effort, the independent system was chosen because it focuses more on improving the generation of the supply side rather than the demand or load side. As shown in the form.

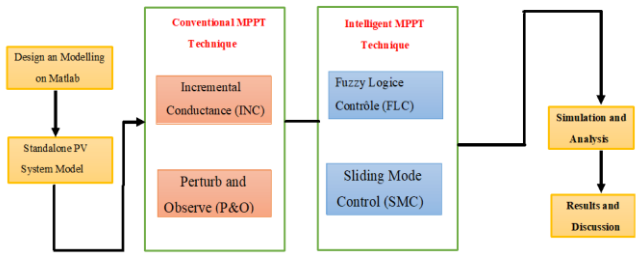


Fig. 9. Methodology flowchart is displayed

3.1. P&O Methodology

The traditional P&O approach can become unstable when irradiance fluctuates quickly, and the tracking performance is strongly influenced by the step-size. This section presents a rough explanation referred to as the modified P&O technique of the link between step-size and MPPT performance [15]. Consistent current and voltage perturbation of the PV system is carried out with this MPPT approach. When power increases, or when $\Delta P > 0$, the perturbation that follows stays in that direction until it reaches the maximum power point (MPP). However, the direction of perturbation is reversed if a drop in power, $\Delta P < 0$, is monitored. The MPO MPPT algorithm is shown in Fig. 10.

3.2. The approach for the incremental conductance (IncCond)

The following equation is the foundation of the Incremental Conductance (IncCond) algorithm and is held at the MPP [3].

$$\left(\frac{dI}{dV}\right) + \left(\frac{I}{V}\right) = 0;\ dI/dV + I/V < 0 \quad (12)$$

The operating point is located on the right of the MPP while it means that the voltage must be reduced to reach the MPP. Similarly, $dI/dV + I/V > 0$ if once the operating point is to the left of the MPP. Thus, the operating voltage must be increased to reach the MPP [27]. Figure 11 shows the organizational chart of the INC algorithm. Thus, the right direction of perturbation leading to the MPP is indicated by the sign of the amount $(dI/dV) + (I/V)$. Therefore, it is theoretically conceivable to determine when the MPP has been reached and, consequently, when the perturbation can be halted using the IC algorithm. In situations where atmospheric conditions are changing quickly, the IC technique performs well. Fig. 11 shows the algorithms INC.

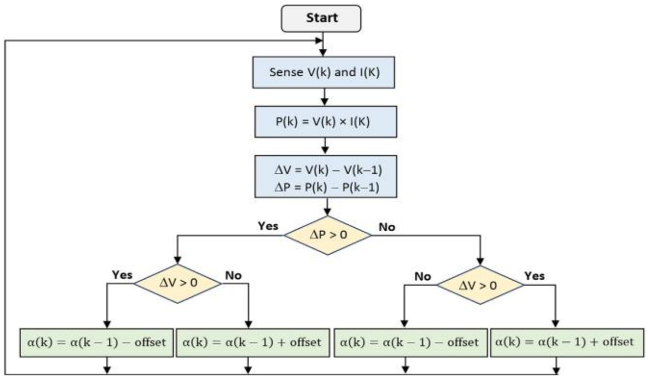


Fig. 10. Schematic depicting the P&O algorithm

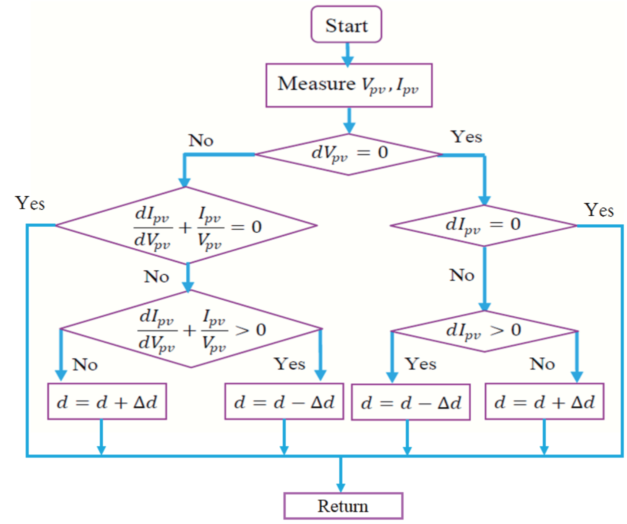


Fig. 11. Diagram illustrating the incremental conductance technique

3.3. Simulation results

In Matlab, P&O MPPT and Wince MPPT are implemented through custom coding and using the function block built as shown in Fig. 12. Variable test conditions (temperature and irradiance) are subjected to the INC MPPT and P&O MPPT algorithm to determine how long it takes to track the MPP and continue to extract the maximum power.

Fig. 13 shows the change in irradiation and temperature applied in this research. The variable values of radiation and temperature are presented in Table 2.

Test 1 is a change in the irradiance 1000 W/m^2, the temperature is constant T = 298 K (25°C), where the irradiance settles for 0.5 s as shown in Table 5 and then diminishes to 800 W/m^2 and settles in the interval [0.5 s, 1 s] after which it is reduced to 600 W/m^2 and fixed in the interval [1 s, 1.5 s]. The latter is stable during two times [1.5 s, 2 s] with a value of 1000 W/m^2.

Test 2 is a change in temperature and with fixed irradiance of 1000 W/m^2 where the temperature stabilizes at a value of 25°C for 0.5 s as shown in Table 5 and then rises rapidly to a value of 45°C and stabilizes in the interval [0.5 s, 1 s] and then drops to 30°C and is fixed in the interval [1 s, 1.5 s]. The latter is stable over two periods [1.5 s, 2 s] with a value of 25°C.

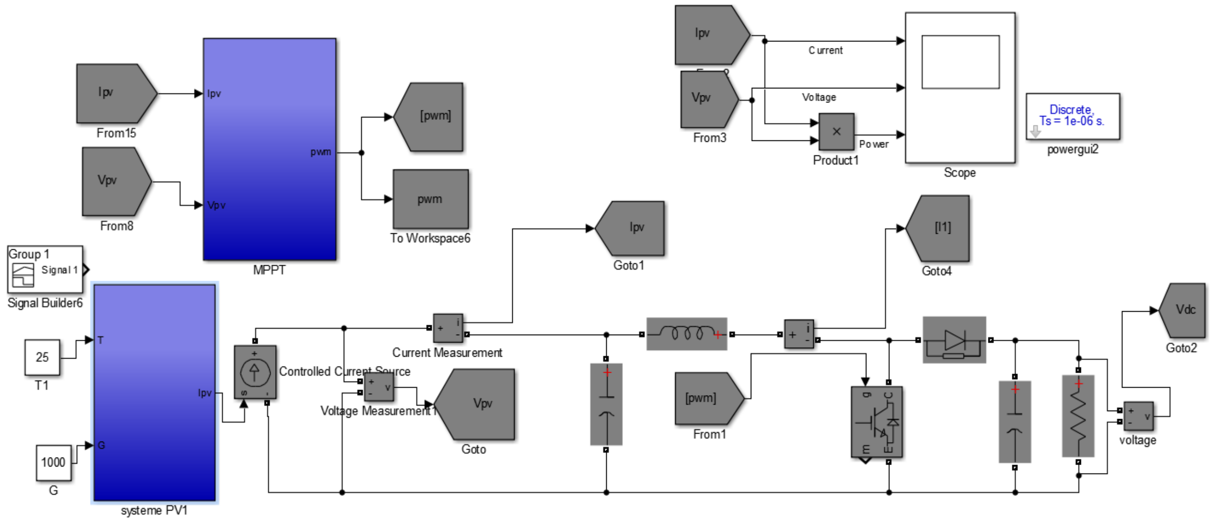


Fig. 12. PV system diagram with MPPT control in Matlab Simulink

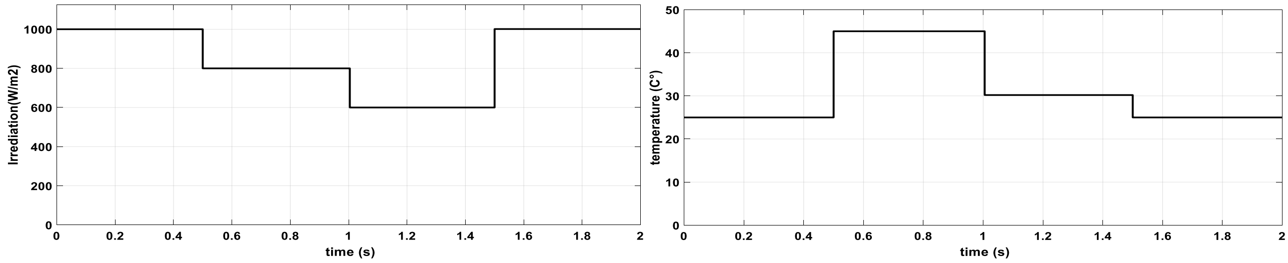


Fig. 13. Irradiance and temperature change

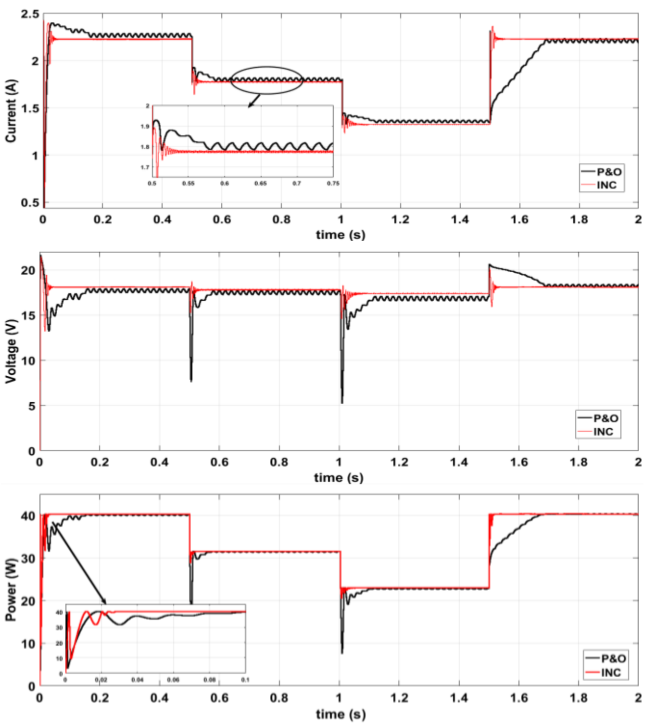


Fig. 14. The simulation results are energy, current and tension with P&O and INC under variable irradiance

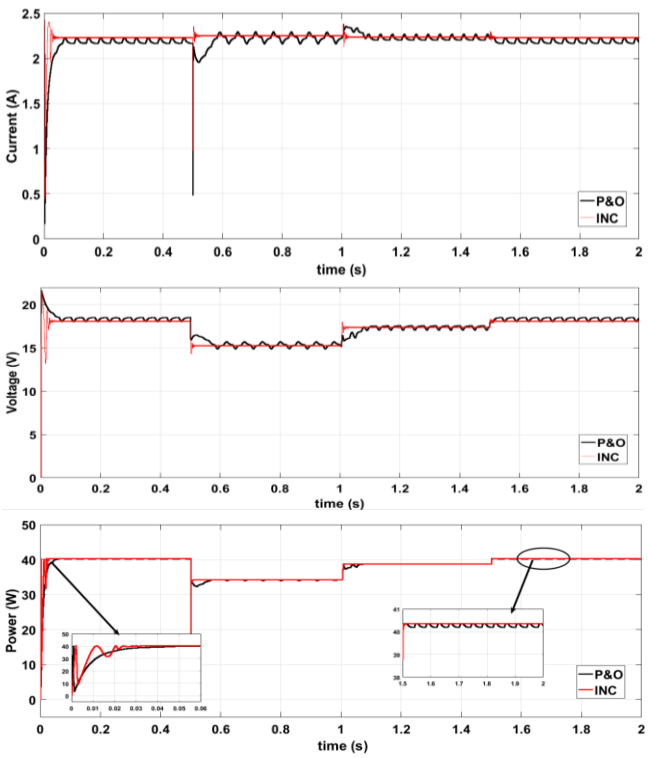


Fig. 15. The simulation results are current, voltage and power with P&O, INC under variable temperature

Table 5. The varying irradiance and temperature

Time (s)	Irradiance (W/m^2)	Temperature (°C)
0-0.5	1000	25
0.5-1	800	45
1-1.5	600	30
1.5-2	1000	25

The power extraction results of the INC MPPT and P&O MPPT algorithm are shown in Fig. 14. It takes INC MPPT 0.025 s to track the MPP and perform the extraction of the remaining energy, while P&O MPPT takes 0.15 s as can be seen. Fig. 15 shows the effect of temperature on the output of a photovoltaic cell (Current, Voltage, Power). Where P&O technology takes 0.05 s or INC takes 0.025 s. In situation with rapid changes in irradiance and temperature, INC surpasses P&O thanks to its accuracy in calculating instantaneous changes in voltage and current. While P&O may be delayed in responding to rapid changes, which leads to a decrease in efficiency in such conditions.

INC reacts faster and more accurately to sudden changes, such as cloud transitions in solar energy systems or temperature changes. It provides higher stability at MPP due to the fact that it relies on the most accurate calculations to determine which point achieves maximum capacity

P&O can lead to small vibrations around the maximum power point due to the nature of the method that uses changes in voltage to observe changes in power. This leads to a constant error about the MPP point.

4. Sliding mode controller technique

It's among the most effective nonlinear control techniques. The DC-DC converter's SMC controls the MPPT controller based on SMC, which permits MPP in different weather circumstances. More switching would voltage and power output oscillations grow along with the MPP tracking speed.

The performance of the SMC-based MPPT is better than that of other traditional approaches [1, 14]. It is necessary to impose the restriction that system variables must stay within a preset range when using a control formula, more especially for sliding mode control (SMC) [4].

$$\dot{x} = f(x,t) + g(x,t)u(t) \tag{13}$$

The sliding surface S's derivative (x, t) is as follows:

$$\dot{S} = \frac{ds(x,t)}{dt} = \frac{1}{dt}\left(\frac{\partial s}{\partial x}dx + \frac{\partial s}{\partial t}dt\right) = \frac{\partial s}{\partial x}\dot{x} + \frac{\partial s}{\partial t} \tag{14}$$

The matching control equation and discontinuous control for the sliding surface sign have an impact on the sliding mode control of the system U_n.

$$U = U_{eq} + U_n \tag{15}$$

(U_n) in order to satisfy the convergence requirement, the control variable, is selected in a way that appeals to the sliding surface.

$$S(x) \cdot \dot{S}(x) \prec 0 \tag{16}$$

where U_n is expressed as follows:

$$U_n = -K_{eq} Sgn(S(x)) \tag{17}$$

The boost converter duty cycle is dynamically altered using the sliding mode control method in order to track the MPP.

$$\frac{dP_{pv}}{dV_{PV}} = I_{PV} + \frac{dI_{PV}}{dV_{pv}} V_{pv} \tag{18}$$

Switch functions come in a variety.

$$S(x) = \frac{dP_{pv}}{dV_{PV}} = I_{PV} + \frac{dI_{PV}}{dV_{pv}} \tag{19}$$

The analogous control is:

$$U_{eq} = 1 - V_{pv} / V_{dc} \tag{20}$$

Contrasting the voltage of the PV panel with that of the load yields, the boost converter duty ratio is:

$$U = 1 - \left(V_{pv} / V_{dc}\right) - K_{eq} Sgn(S(x)) \tag{21}$$

Variations in the reference and PV voltages are among the inputs used by the controller; the output of the sliding mode control determines the duty cycle.

Results and discussion

In this section, three technologies P&O, INC, SMC were compared and the system was modeled using matlab/simulink. The same irradiance and temperature variation used in the previous penalty was applied.

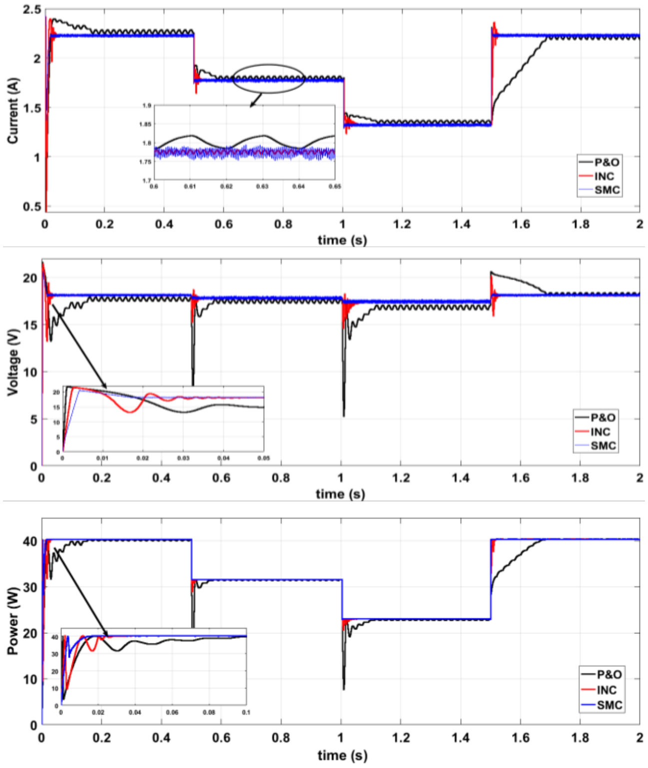


Fig. 16. The output performance of the photovoltaic cell: current, voltage and powerin a variable irradiance mode

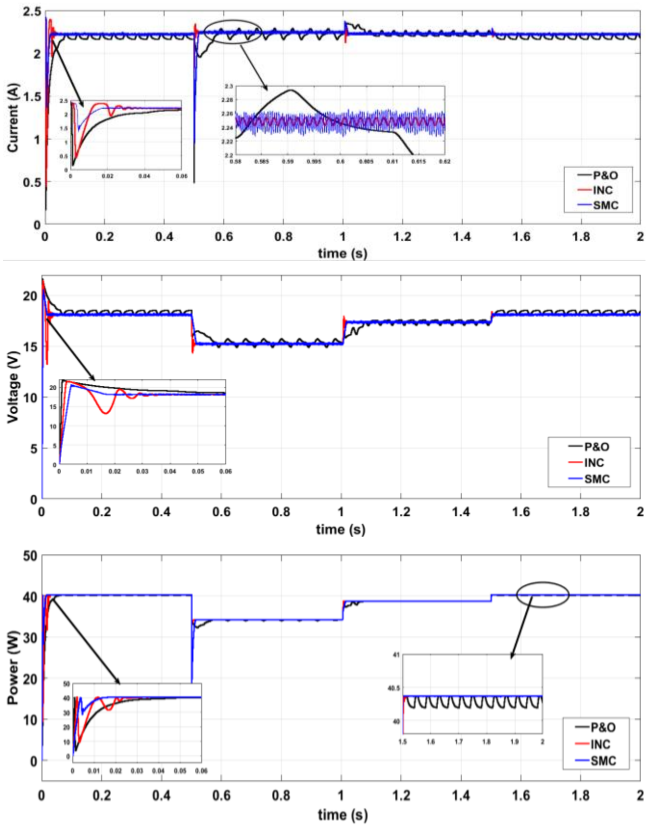


Fig. 17. The output performance of the photovoltaic cell: current, voltage and energy at a variable temperature

Table 6. Response time per Technology

Time (s)	Irradiance (W/m^2)	P&O	INC	SMC
0–0.5	1000	0.15 s	0.025 s	0.015 s
0.5–1	800	0.56 s	0.515 s	0.5 s
1–1.5	600	1.1 s	1.03 s	1 s
1.5–2	1000	1.65 s	1.52 s	1.5 s

Fig. 16 and 17 shows the results of the effect of the irradiance change on the outputs of the photovoltaic cell (current, voltage and power). The response time results for each technique are shown in Table 6. Note that all techniques enable tracking the maximum power point, but with varying response times, as shown in Table 6.

P&O technology shows vibration in the results in contrast to INC technology, which showed constancy in response. As for SMC technology, it showed high response speed and excellent stability during changing weather conditions, but it suffers from the phenomenon of chatter the results also show that the tension is not affected by a change in irradiance, and you can see that a change in irradiance affects the current and energy.

In most cases, increasing the light can lead to a slight increase in the open voltage, but this change is insignificant compared to current changes. Solar cells are usually designed so that the voltage is constant within a certain range of irradiance. Unlike a change in temperature, as an increase in temperature may slightly reduce the voltage

5. Power fuzzy controller synthesis

Due of fuzzy logic controller's effectiveness and fuzzy logic controllers have grown increasingly common in the last few years used quite successfully in a wide range of industrial applications [15].

Because of FLC uses natural language and human reasoning [17], fuzzy logic-based MPPT trackers have demonstrated extremely good performances under varying temperature and irradiance circumstances. To choose the right fuzzification, inference mechanism, rule basis and defuzzification methods, excellent design is necessary [17]. The inputs of fuzzy controller are error (e) and its derivative (de).

Fig. 9 provides a general breakdown of the blurring controller's architecture. The error (e) and its derivative which are the two inputs for this controller, have through three steps of information processing: fuzzification, défuzzification, and inference to produce the output (du). The following is a summary of each block's function [11].

The power and voltage derivatives (dP_{PV}/dV_{PV}) in our instance are the blur regulator's inputs [11], as seen in Fig. 13, together with the error and its variation in the subsequent equations:

$$e_{pv}(K) = \frac{p_{pv}(K) - p_{pv}(K-1)}{v_{pv}(K) - v_{pv}(K-1)} \quad (22)$$

$$de_{pv}(k) = e_{pv}(K) - e_{pv}(K-1) \quad (23)$$

The blur controller's language variables are described as follows: The association between inputs and outputs is (PB: Positive Big, PS: Positive Small, Z: Zero, NS: Negative Small, NB: Negative Big).

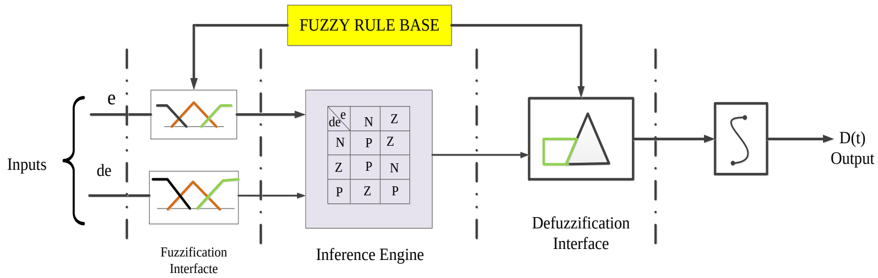


Fig. 18. Fuzzy regulator synthesis block scheme

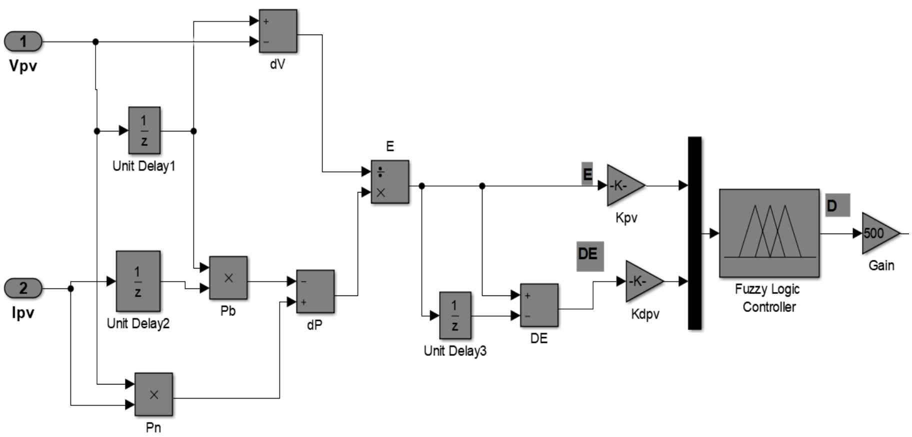


Fig. 19. An overall schematic of a fuzzy MPPT controller

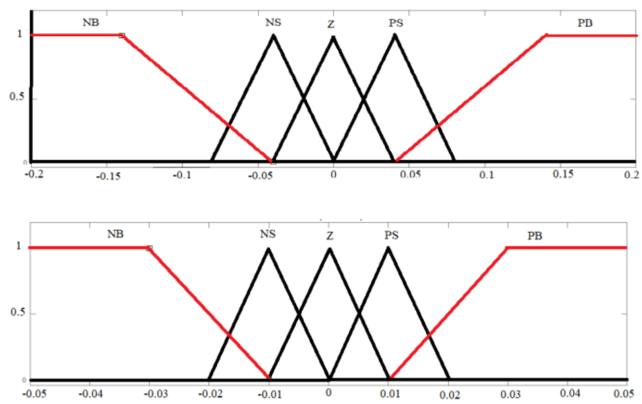


Fig. 20. Membership Function of (ePV, dePV)

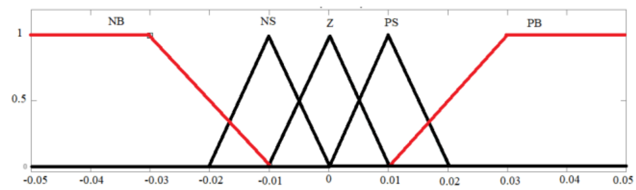


Fig. 21. Membership Function of duPV

5.1. Results and discussion

Comparison between P&O, INC and FLC

The results of the tests of the photoelectric control system by the P&O, INC and FLC controller for two tests are represented in Fig. 16 and Fig. 17.

Fig. 20 and Fig. 22 show the results of the optimal power of the photovoltaic system for variable temperature and Irradiance conditions. Where FLC technology achieves the shortest response time of 0.01 or FINC technology achieved a response time of 0.025 s and P&O technology the longest response time of 0.045 s. The P&O algorithm is a classic and simple technique.

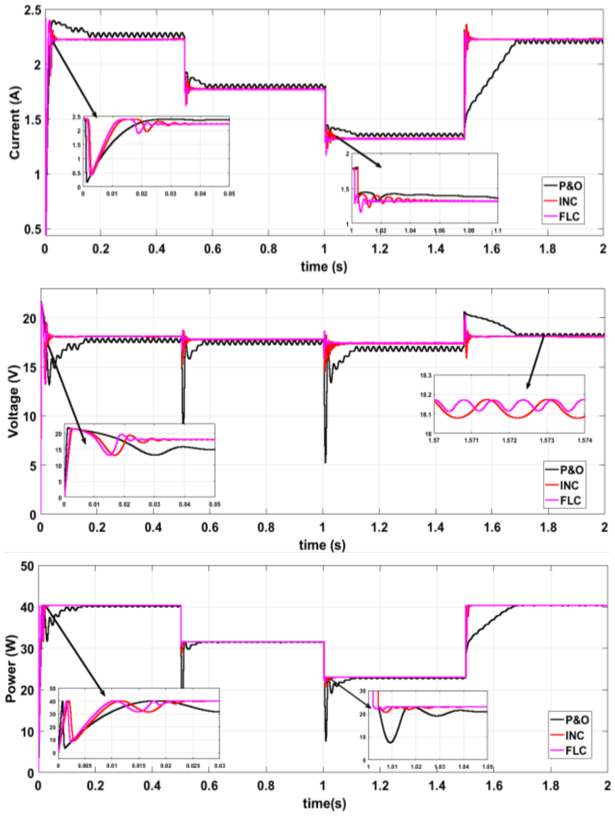


Fig. 22. System performance using P&O and Inco FLC technologies under variable irradiance

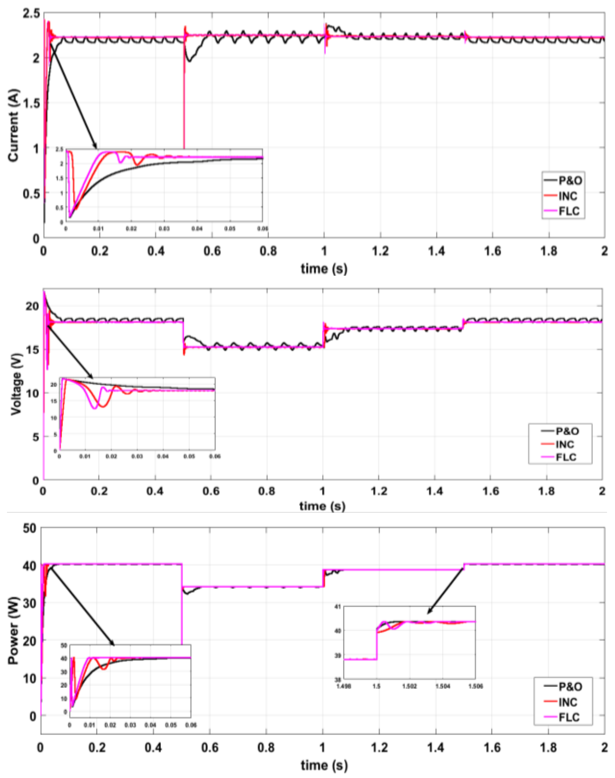


Fig. 23. System performance using P&O and Inco FLC technologies under variable temperature

Table 7. The voltage outputs of FLC, P&O and Winc at specific Irradiance and temperatures

Time (s)	Irradiance (W/m^2)	P&O	INC	FLC
0–0.5	1000	18	18.24	18.24
0.5–1	800	17.8	17.8	17.8
1–1.5	600	17.3	17.5	17.6
1.5–2	1000	18.4	18.24	18.24
Time (s)	T (°C)	P&O	INC	FLC
0–0.5	25	18	18.24	18.24
0.5–1	45	15.4	15.4	15.4
1–1.5	30	17.56	17.49	17.4
1.5–2	25	18	18.24	18.24

This algorithm depends on the initial conditions and shows an oscillation around the value of the Homomorphism. The main disadvantage of this algorithm is its poor behavior afterchanges in atmospheric conditions.

While the INC algorithm behaves better than P&O technology during a change in natural conditions. However, it is a more complex technique than the previous one. FLC technology is considered to be a strong behavior and stability during changing weather conditions. Flexible adaptation to changes. High accuracy in tracking the maximum point of energy.

Table 8 shows the voltage outputs of FLC, P&O and Winc at specific irradiance and temperature.

Table 8. Comparison of response time between technologies tracking the maximum power point (SMC, FLC)

Time (s)	Irradiance (W/m^2)	SMC	FLC	Temp (°C)	SMC	FLC
0–0.5	1000	0.015s	0.02 s	25	0.015 s	0.01 s
0.5–1	800	0.505s	0.5 s	45	0.515 s	0.503 s
1–1.5	600	1.05 s	1. s	30	1.017 s	1.01 s
1.5–2	1000	1.505 s	1.5 s	25	1.506 s	1.506 s

Comparison between FLC and SMC

The results of the tests of the photoelectric control system by the SMC and FLC controller for two tests are represented in Fig. 24 and Fig. 25.

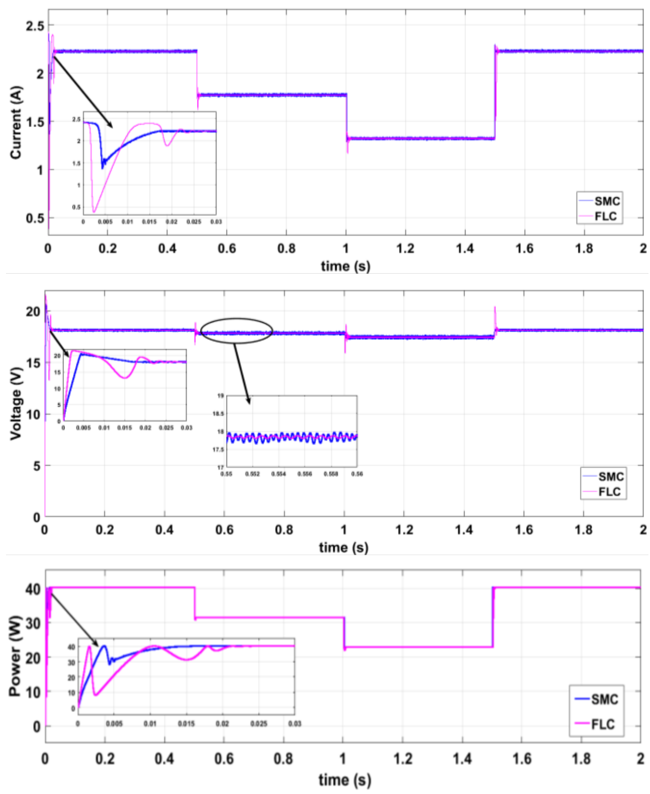


Fig. 24. PV panel current, voltage and power under different levels of irradiance

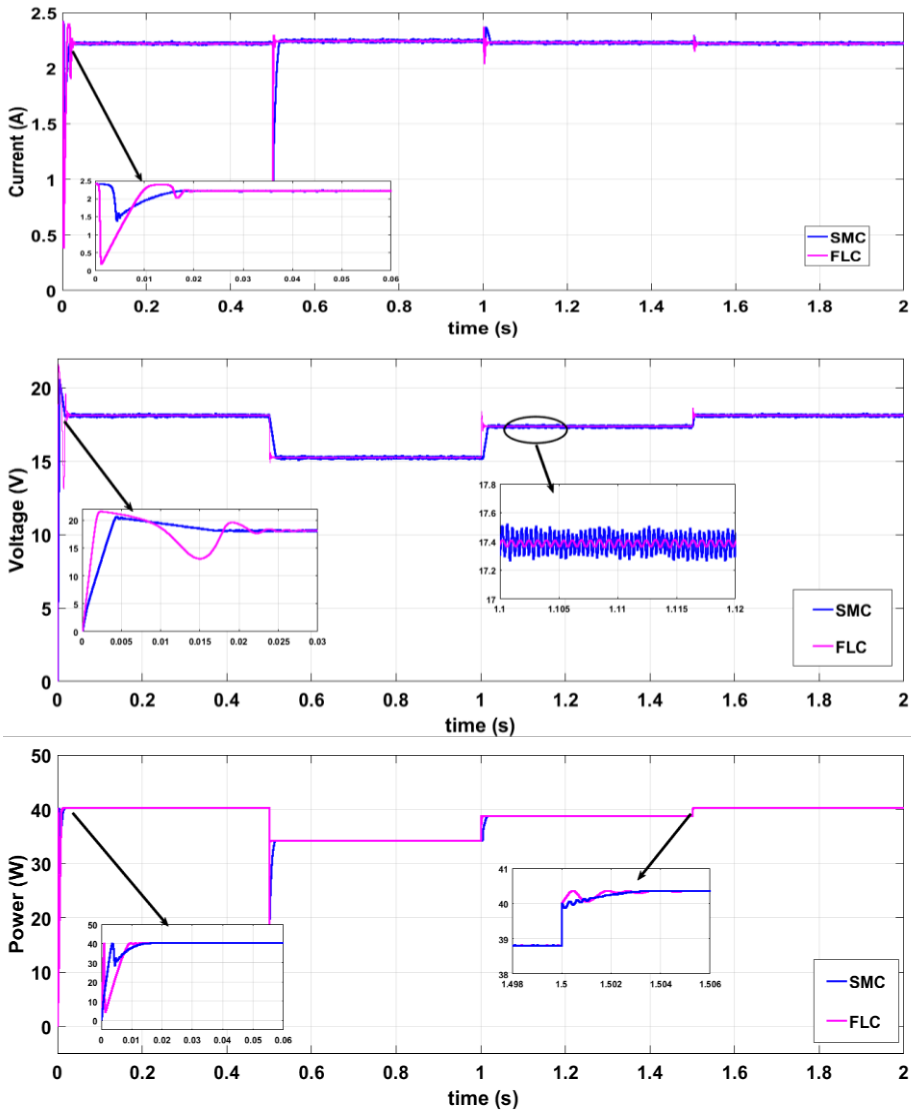


Fig. 25. Temperature variations effects on the current, voltage and power of photovoltaic panels

5.2. Discussion

The results showed that intelligent algorithms not only excelled in energy production but also in tracking speed. The Table 8 table shows the results of the stabilization time and tracking accuracy of the MPPT algorithms. a detailed comparison of sliding mode control technology (SMC) and fuzzy logic (FLC) in the field of maximum power point tracking (MPPT) of photovoltaic cells is presented.

The analysis revealed a clear superiority of fuzzy logic despite the fact that both technologies offer a quick and effective response in the face of environmental changes.

Fig. 25 shows the current, voltage and power output of the photovoltaic panel under variable radiation, a comparison of sliding mode and fuzzy logic control. Both technologies were able to track the maximum power point, SMC achieved a stabilization time of 0.015 s, and fuzzy logic achieved a stabilization time of 0.01 s. Although SMC achieves a quick response, the comparison showed that FLC excels in this aspect. Blur logic relies on flexible rules that can adapt to variables faster, giving it an advantage in rapidly changing environments, such as sudden changes in light intensity or temperature. In turn, while SMC also shows a quick response, in some cases it may experience a slight delay in the system's reaction to environmental changes.

The results show that both technologies are characterized by rapid response and flexibility during atmospheric changes, however, SMC suffers from chatter in its outputs. Such chatter causes undesirable fluctuations in measurements, which can lead to loss of energy and loss of stability in the system.

On the contrary, FLC shows excellent response and superior stability, as it manages to effectively eliminate the chattering phenomenon, which enhances the stability of the system and improves the energy extraction of photovoltaic.

On the other hand, although SMC provides a degree of stability in the face of changes in weather conditions, FLC remains superior in maintaining stability on an ongoing basis.

The ability of FLC to adapt to various environmental changes gives it higher stability and better performance in unstable environments.

The simulation results show that during a change in temperature affects the current, voltage and power for sliding mode and fuzzy logic system. The capacitive voltage decreases with increasing temperature due to increased electron discharge inside the cell.

This reduces the voltage generated while the output current (Isc) increases slightly with temperature, but this is not significant compared to voltage changes. Although the current may increase slightly with temperature, a decrease in voltage leads to a decrease in the total energy extracted from the cell.

High temperature negatively affects the efficiency of photovoltaic cells and reduces their ability to generate energy.

6. Simulation the four controllers and controllers in the following conditions (*T* = 25°C and irradiance *G* change)

We compare the four controllers based on the energy produced by the photovoltaic system under changes in the level of irradiation and a constant temperature at *T* = 25°C. The four controllers were able to track the maximum power point, but with a different response time, We also note the effect of an increase and decrease in the level of Irradiance *G* on the energy produced by the photovoltaic system. By achieving the constant temperature condition as shown in Fig. 26 and 27.

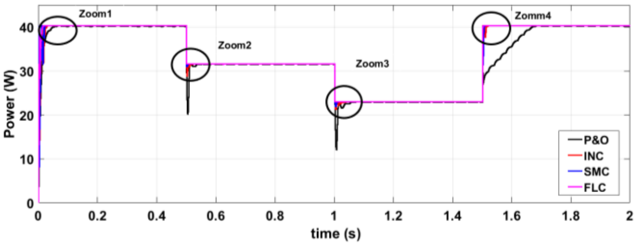


Fig. 26. The variation of the power of the four controllers in the conditions (T = 25°C and variable G)

From Fig. 27a, the response time of the four control units, where we observe that "SMC" is the fastest at 0.015 s, followed by fuzzy logic control at 0.02 s, then INC at 0.02 s, and finally P&O control with a slow response at 0.05 s.

In the "P&O", "SMC", and "INC" controllers have fluctuations in parts per million. They do not provide enough precision, so the system does not operate at the optimal power point perfectly. While the "Fuzzy" controllers are fixed.

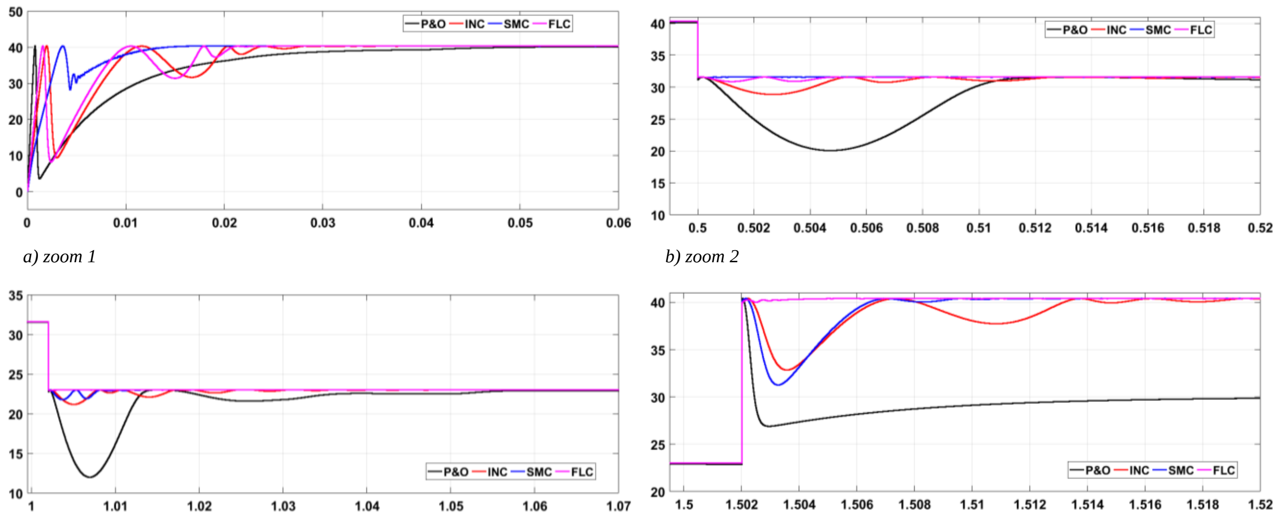
From Fig. 27b, when there is a rapid change in radiation *G* (at *G* = 800 W/m²), we notice that the fuzzy logic controller quickly follows PPM, followed by "SMC" and "INC", and then P&O with a slow response.

When the irradiance *G* is reduced (at *G* = 600 W/m²), we observed that the response time of the "FLC" controller is faster than the response time of the "SMC" and "INC" controllers, while the P&O controller is very slow compared to the others, as shown in Fig. 21c.

In Fig. 27b, when changing of the irradiance level (*G* = 1000 W/m²), the FLC unit gives the best result, followed by "SMC", then "INC", and "P&O", which achieve the longest response times with subsequent oscillations.

Table 9 presents the main specifications of the previously analysed MPPT algorithms. We have evaluated these algorithms and compared them based on the simplicity in implementation.

Accuracy in tracking, responding to sudden changes, complexity of calculations, cost of implementation, stability in unstable conditions and noise in control.



a) zoom 1 b) zoom 2

c) zoom 3 d) zoom 4

Fig. 27. Zoom the power variation of the four condition controllers (T = 25°C and variable G)

Table 9. Complexity comparison all techniques follow the maximum power point

Criterion	P&O	INC	SMC	FLC
Simplicity in implementation	Simple and easy to implement	A little complicated compared to P&O	Highly complex	Complex and requires logical knowledge
Accuracy in tracking	Less accurate in rapid changes	High accuracy in changing conditions	Excellent accuracy, noise resistance	Very high accuracy
Response to sudden changes	Low performance in sudden changes	Good response, especially in changing light	Fast and accurate response	Flexible and fast response
Complexity of calculations	Low	Average	High	High
Cost of implementation	Low	Average	High	High
Stability in unstable conditions	Low	Good	Excellent	Excellent
Noise control	Prone to noise	Good	Excellent	Good

7. Conclusions

The study reveals that different approaches follow MPP in different periods. However, the FLC MPPT system achieves a stable state faster than other tracking strategies, while the P&O method is slower when the radiation changes rapidly.

FLC provides fast movement of the operating point towards the MPP, which reduces the loss of energy from the search process.

The durability of the proposed approach is confirmed by the results obtained and previously presented, showing power and voltage responses during rapid temperature fluctuations.

The FLC-MPPT and SMC algorithm has successfully achieved the maximum power point with much better performance than INC WP&O technologies. It performed better in all scenarios in terms of performance metrics such as override values and settlement time.

The creation of photovoltaic energy as a viable energy source on the market largely depends on its efficiency, stability and reliability.

One of the most important reasons why photovoltaic has become a market leader is its efficiency, reliability and stability.

In this research we studied and compared several popular techniques for tracking the maximum power point using classical algorithms (P&O, INC) and modern algorithms that attracted researchers (SMC, FLC).

From this lesson, we conclude that the foggy mode (FLC) is one of the algorithms that managed to improve stability and increase the reliability of photovoltaic energy conversion especially in the event of a sudden change in weather conditions. In the future, we are looking forward to achieving a couple (SMC-FLC).

Fuzzy-sliding mode control (FSMC) technologies in order to optimize solar PV systems using controllers that are better compatible.

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Eng. Khoukha Bouguerra
e-mail: bouguerra.khoukha@univ-setif.dz

Born in Bordj Bou Arreridj, Algeria. She obtained his engineering degree from Mohamed Bachir El Ibrahimi University, Bordj Bou Arreridj, Algeria, in 2017. She is pursuing her Ph.D. studies in Industrial Automation and Computer Engineering from the Department of Electrical Engineering, Ferhat Abbas University, Setif, Algeria. Her research interests include renewable energy systems and artificial intelligence. She is the author of several publications and international contacts.

https://orcid.org/0009-0008-4522-1532

Dr. Samia Latreche
e-mail: ksamia2002@yahoo.fr

She was born in Setif town – Algeria. She is, since 2016, a Ph.D. at Automatic Laboratory, Electrical Engineering Department, Faculty of Technology, University of Setif (Algeria). She obtained the HDR Degree in 2019. Her main research concern control, fault detection and isolation, identification-based diagnosis. The application domains are mainly process engineering, renewable energies and power systems. Her main research concern fault detection and isolation, identification-based diagnosis. The domain application is mainly process engineering and renewable energies. She is the author of 29 publications and 90 international communications.

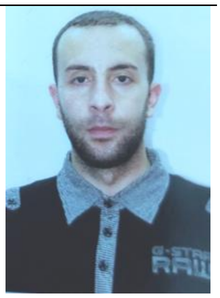
https://orcid.org/0000-0002-1496-739X

Prof. Mabrouk Khemliche
e-mail: mabroukkhemliche@univ-setif.dz

He was born in Setif – Algeria. He is, since 2012, Professor at Electrical Engineering Department of Setif (Algeria). He heads the Automatic Laboratory of Setif-LAS and the Monitoring team of LAS laboratory. His main research areas concern Diagnosis and Control in Electrical and Process Engineering systems using new technologies, artificial intelligence by analytical and graphical approaches. Their application domains are mainly nuclear, renewable energy, thermo fluid and petrochemical processes. He is the author of more than 150 international publications and communications.

https://orcid.org/0000-0002-1448-3010

Mr. Hamza Khemliche
e-mail: h.khemliche@crti.dz



He was born in Setif – Algeria. He is senior research engineer at the Research Center in Industrial Technologies – CRTI (Algeria). He is head of the IT cell at the additive manufacturing research unit – URFA. His main research areas concern Simulation, Modeling and Monitoring of Computer Science Systems. Their application domains are sensor networks, renewable energy and additive manufacturing. He is the author of many international publications and communications.

https://orcid.org/0000-0002-7373-780X