Fuzzy Sliding Mode Control of the Photovoltaic System Connected to the Network

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Abstract: - To maximize the conversion efficiency of photovoltaic power systems, it is necessary to design a controller to track the maximum power points used to extract maximum power from photovoltaic systems. In this paper, a maximum power point tracking MPPT strategy based on fuzzy sliding mode control FSMC connected to the photovoltaic system interconnected to the grid has been applied. The main concept of the proposed method is to combine the sliding mode control SMC and the performance of fuzzy logic control FLC to increase the power generated for a certain set of weather conditions. The system consists of a photoelectric generator followed by a DC/DC converter and DC/AC inverter. The main development of the proposed technique is to combine the advantages of FLC and SMC in an algorithm that directly controls a DC/DC converter to track the maximum power point and control it well. The MPPT methods considered in this study include perturbing and observing algorithm P&O, fuzzy logic control FLC, sliding mode control SMC, and fuzzy-sliding mode control FSMC. The photoelectric model, DC/DC, and DC/AC power adapter are designed under Matlab/Simulink environment. The simulation results confirm the effectiveness of the proposed method and prove that it can work reliably under various conditions.

Key-Words: - Fuzzy logic-sliding mode control, Photovoltaic system, DC/DC converter, DC/AC inverter Maximum power point tracking, Perturb and observe algorithm, Fuzzy logic control, Sliding mode control.

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1 Introduction

Efficiency is generated by photovoltaic generators (PVG) as the demand for solar energy continues to rise. We can harness the sun's unlimited supply of energy to our great advantage for a very long time. Simply put, solar photovoltaic energy is obtained by converting the energy carried by photons in light into electricity. A photoelectric cell is made of Silicon, when exposed to light it absorbs the energy of photons. The latter generates a direct electric current, which will be converted to alternating current using an inverter. This immediately produced electricity can be used to power appliances or lighting. PVG has two disadvantages:

- The resulting energy characteristic depends on such environmental conditions as the change in the level of solar irradiance, temperature, and partial shading.
- The low conversion efficiency, especially under low irradiance, [1].

The photovoltaic system may be configured to function at its maximum power points without any prior knowledge of these points thanks to maximum power point tracking (MPPT) controllers, which can also be used to adjust the operating points in response to changing weather conditions. The idea of maximum power point tracking (MPPT) is to track a nonlinear electric generator's MPP and use that information to push the generator to run at maximum power. Actually, this procedure enables the cell to produce its maximum energy, [2], [3], [4].

In addition, unconventional technologies such as the fuzzy logic controller (FLC) and the sliding mode controller (SMC) have been used in the literature.

Despite its outstanding performance, SMC has a chattering phenomenon that leads to overheating of electrical power systems.

Several strategies have been put forward to reduce chattering capacity, such as changing the boundary layer around the sliding surface and selecting the appropriate intermittent sector gain for SMC using innovative methods such as genetic algorithms (GA) to reduce the chattering problem in SMC.

One of the popular ways to track MPP is fuzzy logic control. It is immune to disturbances and works very well. However, configuring and setting up a large number of rules in FLC requires a large amount of memory and processing time, which means that a trade-off between accuracy and speed will always be made, so the association with the sliding mode control can remedy this drawback, [5], [6], [7].

To address the drawbacks of traditional approaches and reach the solar system's maximum power point, the sliding mode microcontroller was employed in this work. The planned strategy has two components. A fuzzy controller with 25 bases is used in the first half to handle the SMC equivalent control, and a fuzzy controller SISO with simple input and simple output is used in the second part to approximate the optimal value and obtain the SMC conversion controller.

Thus, the Matlab/Simulink application was used to construct and test the controller FSMC under various scenarios. To illustrate the performance of the suggested structure, comparisons between P&O, SMC, and FLC technologies were made. The findings demonstrated that the suggested controller performed well in terms of convergence and time response, [8], [9], [10].

The controllability of the grid-connected photovoltaic system is a challenge due to the natural variables and the need to meet grid standards. Network codes are aimed at achieving durability, high-quality, injected network power and fast control. The DC/DC converter on the input side and the DC/AC inverter on the output side are the two phases that make up the typical photovoltaic system.

The DC/DC converter extracts the maximum power MPP and reaches MPPT. At the same time, the DC/AC inverter transfers the extracted power to the distribution network. The DC-link capacitor regulates the voltage, acts as an energy storage capacitor, limits fluctuations, reduces ripple, and allows instantaneous power replacements.

The DC/AC inverter stage performs other tasks, including reactive power compensation, a synchronization, a detection of assembly, and providing high-quality power to the grid. The full bridge DC/AC inverter is used in the second power stage to modulate the first stage's DC input into AC output for the utility grid, harvesting maximum power and supplying it to the grid. A phase locked loop is used for synchronization (PLL).

2 Problem Formulation

2.1 Mechanism of Control of PV Array

Two basic categories can be used to classify photovoltaic system that now exists in the literature:

- Single-phase photovoltaic system, which uses the phase of a single DC transformer;
- Two-phase photovoltaic systems, in which the utility network is connected to the photovoltaic system using an alternating DC-to-DC and DC-to-AC transformer phase. The phase studied in this paper for a photovoltaic system is illustrated in Figure 1.

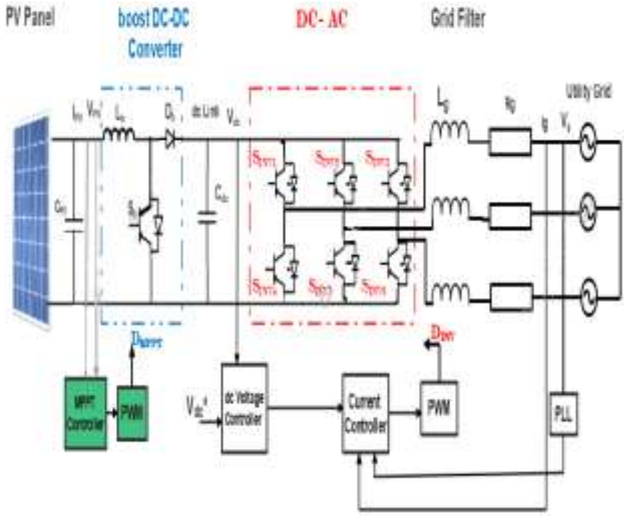


Fig. 1: Control mechanism of photovoltaic system

Firstly, the maximum amount of energy can be extracted from the photovoltaic module using a DC boost converter. The enhanced power adapter has the advantages of constant current from the side of the photovoltaic panel, fewer components, and voltage enhancement. The PWM modulator, which converts the MPPT signal into Gate pulses of the DC/DC boost converter, provides the MPPT with step control.

Secondly, a DC/AC inverter with a full bridge is usually used. The adjustment of the DC input of the first stage to the AC output of the utility network is the responsibility of this step. Using this method, the utility network receives the largest amount of electricity consumed so the current controller calculates the reference current, [5].

2.2 PV Array Model

Changes in temperature, irradiance levels, and field variables such as the angle and position of the sun affect the amount of electricity generated by the photovoltaic array, [10].

The single photovoltaic cell model based on diode has been widely used. In the literature for modeling photovoltaic cells, a current source model depicting a photovoltaic cell is shown in Figure 2.

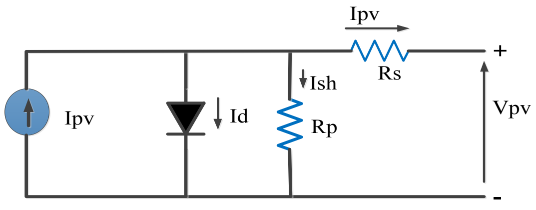


Fig. 2: Electrical model of the photovoltaic cell

The following equations provide the mathematical description of the one-diode electrical circuit:

$$I = I_{ph} - I_0 \cdot \left[\exp\left(\frac{q.(V_{pv} + I.R_S)}{n.K.N_s T}\right) - 1 \right] - I_{sh} \qquad (1)$$

The photovoltaic current of a photovoltaic cell is affected by the amount of irradiance and temperature:

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

The following is how temperature T affects the reverse saturation current I_0:

$$I_0 = I_{rs}.\left(\frac{T}{T_n}\right)^3.\exp\left[\frac{q.E_{g0}.\left(\frac{1}{T_n} - \frac{1}{T}\right)}{n.K}\right] \qquad (3)$$

E.g.: represents the band gap energy of a semiconductor, which is the saturation current at the reference temperature.

$$I_{rs} = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{n.K.N_P T}\right) - 1} \qquad (4)$$

While I_{ph} and I_o symbolize respectively optical currents and saturation, V_t symbolizes the thermal voltage of the photovoltaic cell, which is the ideal factor for a diode. These values correspond to the output voltage and current of the cell.

However, the parallel and series resistances of the photovoltaic cell are referred to as R_p and R_s. Where q represents the electron charge K_B is the Boltzmann constant in a series of cells N_s and N_p is the number of parallel chains (Table 1).

The global model takes into account the number of cells in series *Ns* and the number of cells in parallel *Np* in a module and the same for the panel which is composed of *Ns* modules in series and *Np* modules in parallel, the model then becomes:

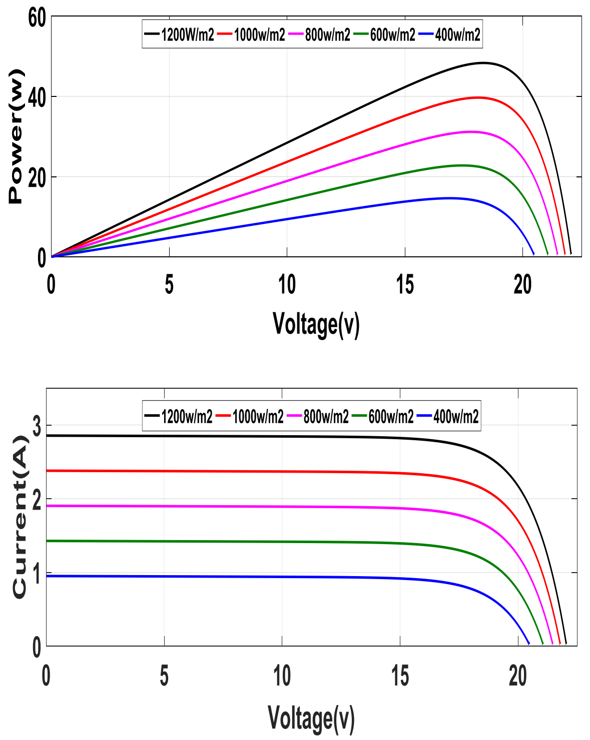
$$Ipv = NpIph - NpIo\left(e^{\frac{NsVpv+(Ns/Np)RsIpv}{nNsVt}} - 1\right) - \frac{NsVpv+(Ns/Np)RsIpv}{(Ns/Np)Rsh} \qquad (5)$$

Table 1. Electrical specifications of the PV module

Parameter	Description	Value	Unit
Pmp	Rated power of PV panel	40	*W*
Vmp	Voltage at MPPT	18.24	*V*
Voc	Open circuit voltage	21.8	*V*
Imp	Current at MPPT	2.20	*A*
Ioc	Short circuit current	2.35	*A*
Ncell	Number of series cells	35	
Rp	Shunt resistance	900	Ω
Rs	Series resistance	0.0035	Ω

The photovoltaic generator exhibits nonlinear behavior influenced by irradiance and temperature. The output power increases with irradiance and that while the open circuit voltage increases slightly. An increase in temperature leads to a decrease in output power.

Photovoltaic curves P/V and I/V indicate the difference in the maximum power points, which requires a control system for effective use as a generator of electrical energy as shown in Figure 3.



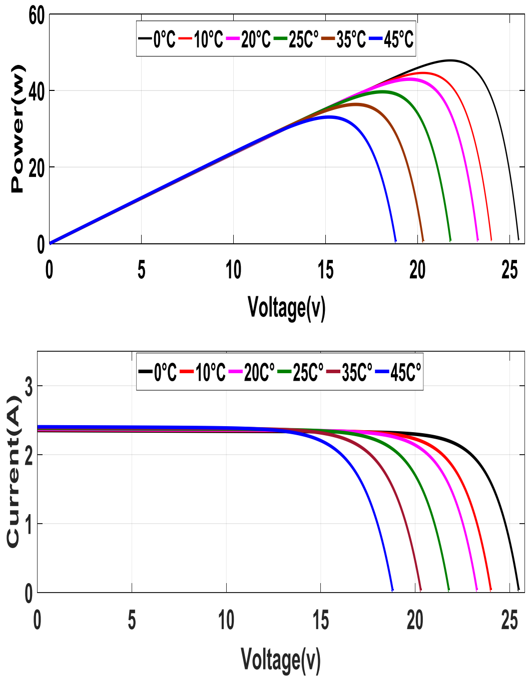


Fig. 3: Characteristics at different temperatures and irradiance levels

2.3 DC/DC Boost Power Converter

Due to its efficiency and ease of use in converting a low DC input voltage into a larger DC output voltage, a boost converter (Figure 4) is one of the most common types of transformers used in renewable energy applications, such as solar and wind energy. The idea is that the MPPT controller generates a Pulse Width Modulation (PWM) signal that controls the converter-switching device, in this example MOSFET, by tracking the maximum power point of each element in the system, [5], [6].

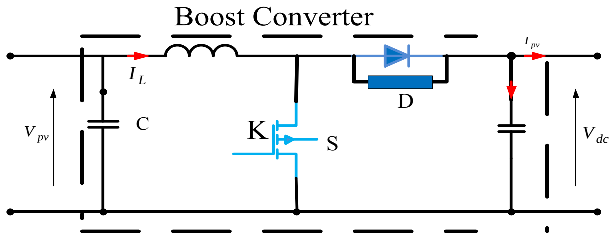


Fig. 4: DC/DC boost converter

$$V_{pv} = L\frac{dI_L}{dt} + V_{dc}\left(1-u_{pv}\right)$$
$$\left(1-u_{pv}\right)I_L = C\frac{dV_{dc}}{dt} + I_{ch} \tag{6}$$

$$\begin{cases} \dfrac{dI_L}{dt} = \dfrac{V_{pv}-V_{dc}}{L} + \dfrac{V_o}{L} u_{pv} \\ \dfrac{dV_{dc}}{dt} = \left(-\dfrac{V_{dc}}{RC_2} + \dfrac{i_L}{C_2}\right) - \dfrac{i_L}{C_2} u_{pv} \end{cases} \tag{7}$$

2.4 DC/AC Inverter Model

The inverter used consists of IGBT-type transistors that are controlled using a Phase-Locked Loop for synchronization (PLL). As shown in Figure 5 it consists of the fewest components.

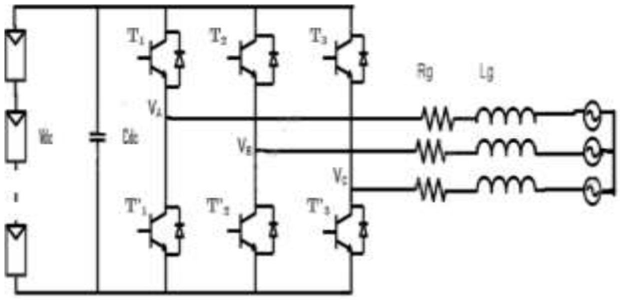


Fig. 5: DC-AC inverter model

This is the voltage vector expression

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{1}{3} \\ \frac{-1}{3} & \frac{2}{3} & \frac{1}{3} \\ \frac{-1}{3} & \frac{-1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} S_1 \frac{V_{dc}}{2} \\ S_2 \frac{V_{dc}}{2} \\ S_3 \frac{V_{dc}}{2} \end{bmatrix} \tag{8}$$

To obtain a sufficiently high voltage, several photovoltaic modules are connected in series. The required sinusoidal voltage is produced by a central inverter, which receives the direct current directly. In addition, in order to disconnect the PV system from the network, an adapter can be installed. If T_i is turned on, then $S_i = 1$, otherwise $S_i = 0$; $_i = 1, 2, 3$.

3 Problem Solution

3.1 MPPT based on P&O Algorithm

The algorithm Perturb and Observe (P&O) is the most often utilized in the MPPT technique due to its simplicity of usage. This technique is predicated on altering the duty cycle of the PV system and then controlling the impact on the generator's output power. In fact, after this disruption, the PV panel's power supply is computed at time k and compared to the prior one at that instant (k - 1).

When the fluctuation of the duty cycle is maintained in the same direction and the difference is positive, indicating an increase in power, we are getting closer to maximum power point. On the other hand, if the difference is negative that is the power decreases, we are moving away from the MPP. Therefore, we have to reverse the direction of the change in the duty cycle.

3.2 Fuzzy Logic MPPT-based

Fuzzy logic is a technique that helps to control problems faster by reducing complexity. It is useful in industrial process control due to its rapid modeling, integration of specialized knowledge, use of variants language, ease of implementation, durability in the face of uncertainty, which makes it a valuable system design tool. It includes three steps: fuzzification, inference and defuzzification.

Fuzzification transforms variables into fuzzy linguistic variables, inference constructs rules and results based on linguistic variables, and defuzzification transforms from linguistic results to numerical results. FLC is a modern artificial intelligence technology that uses fuzzy logic-based MPPT tracker detection of excellent performance under changing irradiance and temperature conditions without any knowledge of the photovoltaic generator model. It involves defining input and output values, converting them to organic values, synthesizing output organic values using extended fuzzy rules, and de-blurring output organic values.

The role of the boost transformer is to continuously follow and deliver the MPP on the DC bus. The fuzzy controller introduces dP_{PV}/dV_{PV} errors and Δ differences, the output of which is the operating ratio of the DC/DC converter or its variation (Figure 6). It considers the duty cycle as its output, and the input variables are defined by (9) and (10) as follows:

$$E_{PV}(K) = \frac{P_{PV}(K) - P_{PV}(K-1)}{V_{PV}(K) - V_{PV}(K-1)} \tag{9}$$

$$dE_{PV} = E_{PV}(K) - E_{PV}(K-1) \tag{10}$$

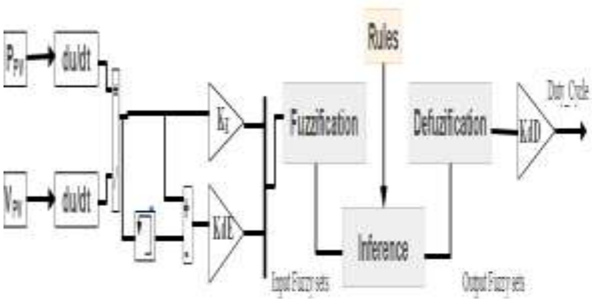


Fig. 6: Building blocks and structure of a FLC

3.3 Sliding Mode MPPT-based

SMC is an effective nonlinear robust control approach that provides system dynamics with the invariant property of uncertainty once the system dynamics are controlled in sliding mode. A non-linear control method manages the DC-DC converter to achieve MPP in changing weather conditions. Its performance is high compared to other classical techniques, since it implements a control equation (11) that forces the system variables to stay on a sliding surface. The advantages of SMC are different: high precision, good stability, simplicity, stability, and durability, [7], [8], [9], [10], [11].

$$\begin{gathered} U = U_{fuzzy} + U_{fsmc} \\ U = U_{fuzzy} + KSat(s(x)) \end{gathered} \tag{11}$$

3.4 MPPT Controller with Fuzzy-Sliding Mode

The fuzzy sliding mode controller is designed for an autonomous photovoltaic system to track the maximum power point, reduce oscillations around MPP, reduce power loss and reduce the chattering phenomenon, which leads to energy losses. Figure 7 shows which part of the control system is used.

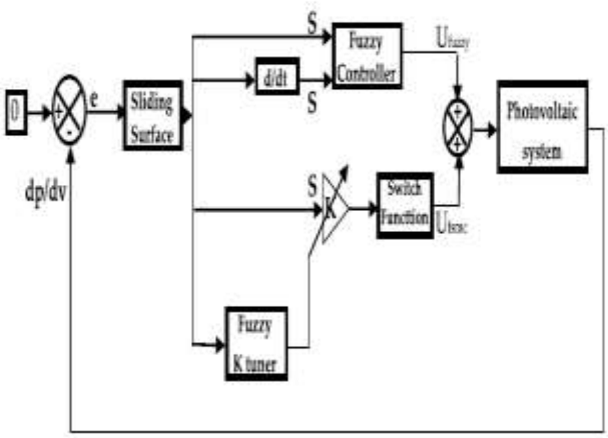


Fig. 7: Structure of the fuzzy-sliding mode control system

The fuzzy controller used in the first section acts as a similar control that maintains the state of the system, [12]. A non-linear controller is used in the second section to install the control. To maintain the state on the sliding surface s(x) = 0, the fuzzy controller and the sliding mode controller work together as an equivalent control.

3.5 Design of Fuzzy Sliding Mode Controller

The fuzzy sliding mode control is used to improve the performance of the photovoltaic power system under variable solar conditions. It stabilizes the system's responses to disturbances, and the magnitude of the disturbance of the controller in the sliding mode is influenced by the switching gain K, [13]. By adaptive tuning of K, the disorder can be reduced. The controller is based on adjusting the blur parameters that supervise and adjust the gain of the controller in the slip mode [14], [15], [16]. Finally, K becomes K_{fzz} in equation (11), resulting in equations (12) and (13).

$$U_{fsmc} = K_{fzz}.Sat(s(x)) \tag{12}$$

where Sat is the saturation function, given by:

$$Sat(s) = \begin{cases} \frac{S}{\varepsilon} & if \quad |s| < \varepsilon \\ sgn(s) & otherwise \end{cases} \tag{13}$$

ε: is the thickness of the boundary layer. *sgn*: is the signal function. The switching gain K_{fzz} is estimated by the fuzzy inference mechanism to provide insensitivity to the perturbations as well as to correct fuzzy approximation errors, [17], [18]. The fuzzy gain tuner system (Figure 8) uses the fuzzy inference technique to estimate the switching gain of a sliding surface. It is characterized by five fuzzy sets of input and output variables, triangular organic functions, one input (S), and one output (K_{fzz}). It is possible to establish rules for the system because the gain K is larger and smaller near the sliding surface, respectively, [19], [20].

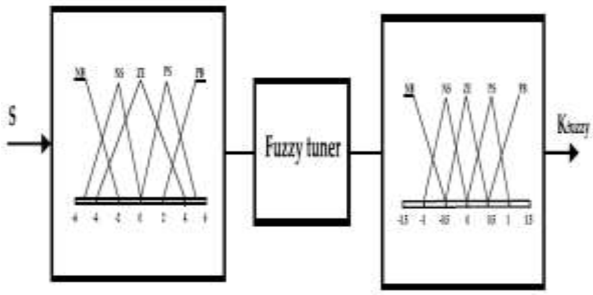


Fig. 8: Structural design of a tuner with fuzzy gain

3.6 Results and Discussion

The study simulated and evaluated four MPPT techniques using Matlab/Simulink software to test the dynamic behavior of a specific photovoltaic system. The proposed control unit was connected, producing 40W at 1000W/m2, and its parameters are presented in Table 1. The parameters of the boost converter are selected as f=10kHz, C_{in}=1000µF, C_{out}=3500µF, and L=190mH.

Different levels of irradiance and temperature were compared to check the power of the control unit. The results illustrated by Figure 10, Figure 11 and Figure 12 showed a difference in the photoelectric output current, voltage and power with the input of progressive irradiance shown in Figure 9.

The change in temperature shown in Figure 13 causes variations of current, power, and voltage of the PV system (Figure 14) and current and charged voltage in the network (Figure 15).

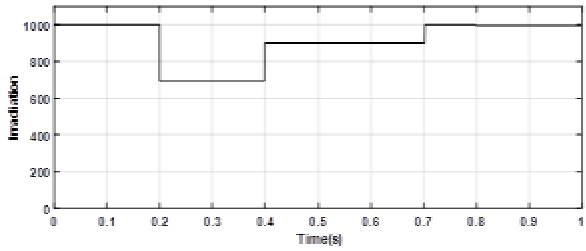


Fig. 9: Change in irradiance

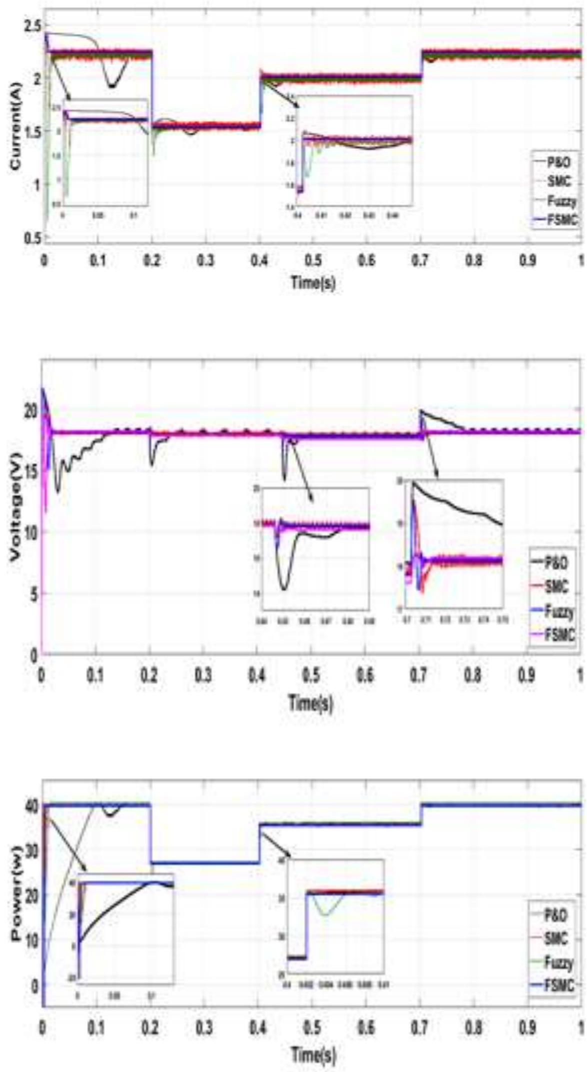


Fig. 10: Current, voltage, and power of the PV system

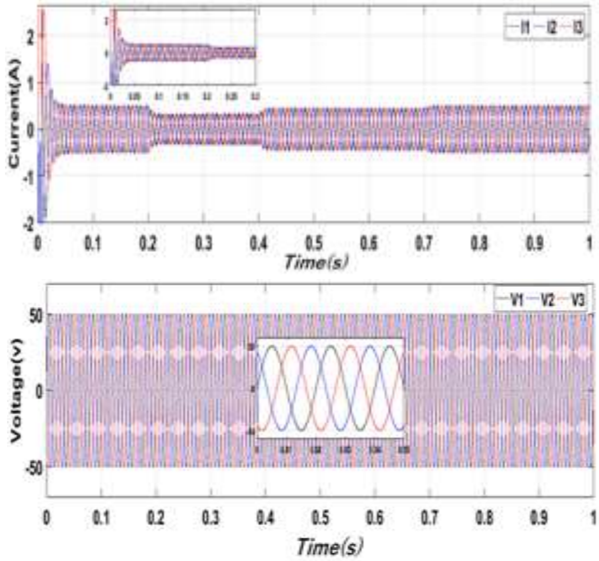


Fig. 11: Charged current and voltage in a network

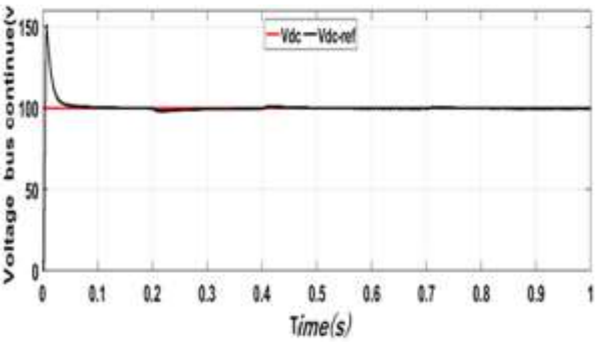


Fig. 12: DC bus voltage (V_{DC} and $V_{DC\text{-}REF}$) due to irradiance changes in the conventional system

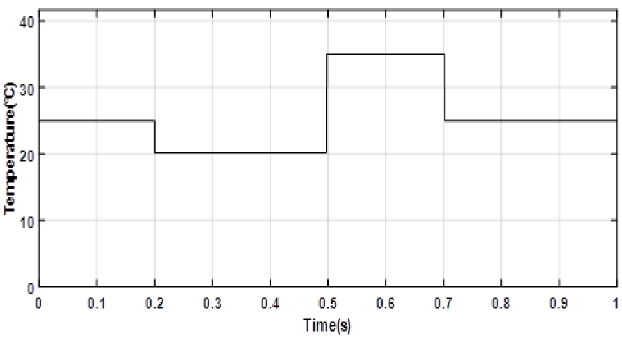


Fig. 13: Change in temperature

According to the simulation results, the photovoltaic power generation system reaches the maximum power point MPP and the required voltage at 0.12s for the control algorithm P&O and 0.005s for the fuzzy-sliding mode algorithm FSMC.

In contrast, the sliding mode controller SMC reached MPP at 0.03s, and the fuzzy logic controller FLC at 0.01s which shows the fast-tracking of MPP and the strong flexibility of uncertainty in the parameters provided by our controller.

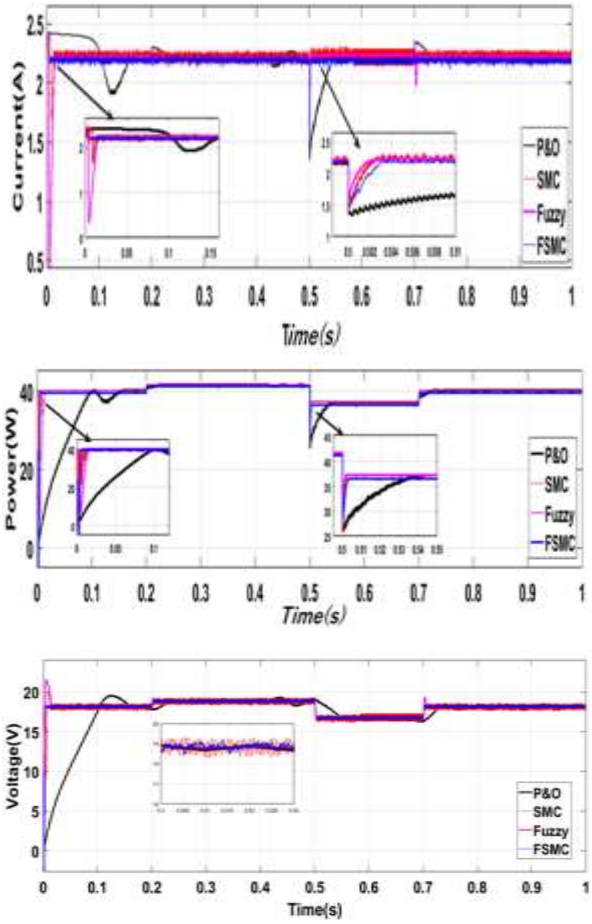


Fig. 14: Current, power, and voltage of the PV system

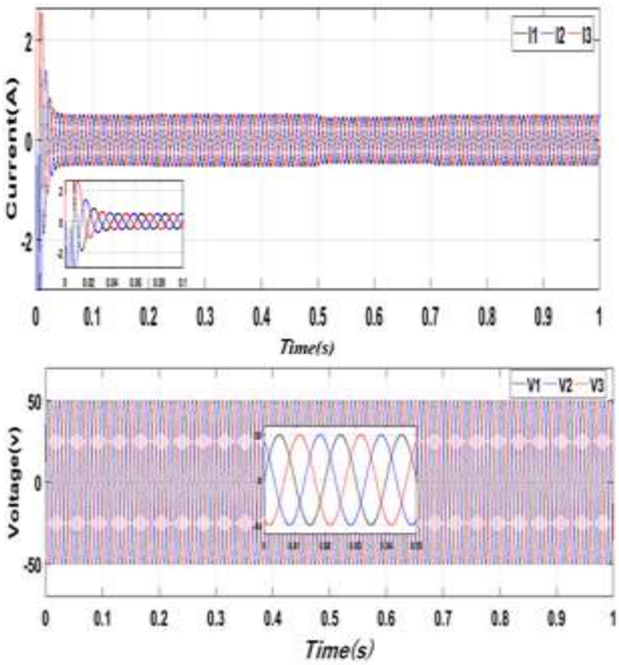


Fig. 15: Current and charged voltage in the network at change of temperature

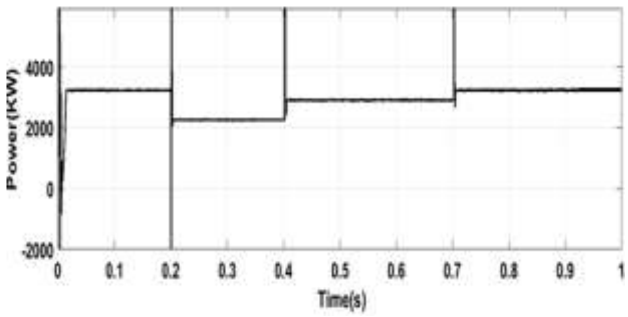


Fig. 16: Fuzzy-sliding mode control's power extraction method

Figure 10 and Figure 14 show the tracking result when changing the irradiance of level 2. When the irradiance level changes sharply in the proposed MPPT controller, the control follows the fuzzy FSMC and the fuzzy logic controller FLC at the speed of the maximum power point.

The algorithm P&O, which occurs at 0.06s before the temperature is varied, is shown in Figure 9.

The study demonstrates that various techniques can track the MPP with different time frames, but the FSMC MPPT-based method achieves a steady state of the irradiance steps faster than other tracking strategies.

The FSMC technique reduces power losses due to search processes and maintains output power at MPP at all time. It overcomes chattering problems and outperforms classical sliding mode controllers.

A comparative study with two algorithms [21] and [22] compared the FSMC technique which combines fuzzy logic and sliding mode control.

The FSMC achieved MPP at 0.005s, demonstrating rapid tracking, high robustness to parameter uncertainties, and reduced oscillation.

Despite the sudden change in irradiance, V_{DC} continues to follow the reference as shown in Figure. 12.

Figure 11 and Figure 15 show the voltages and currents injected into the network. They have a sinusoidal shape and the current is in phase with the voltage during a change in temperature and irradiance.

Figure 16 forces the electrical network in the interval [0 1s] where no load is connected photovoltaic energy (32kW) is fully injected into the electrical network.

It is possible to reduce overtaking and get a very short reaction time (about 0.005s through the use of fuzzy sliding mode control.

Simulation of the parameters that are entered into the network the currents and voltages injected into the network are shown in Figure 10 and Figure 15. Current and voltage are parallel in phase, have a sinusoidal shape.

4 Conclusion

Fuzzy Logic handles uncertainty, making it suitable for solar applications where environmental conditions are constantly changing. It simplifies design and allows for better adaptation to changes in conditions.

Sliding control offers high stability, dynamic control, and noise tolerance, even under large turbulence or sudden changes.

Fuzzy Logic and Sliding Mode Control (FSMC) are two advanced methods used in maximum power point tracking (MPPT) in solar energy systems. FSMC combines the benefits of both technologies, enhancing performance by combining the accuracy of fuzzy logic with the stability of sliding control. It also improves dynamic response to solar energy changes and reduces concussions caused by rapid environmental changes.

FSMC is used in solar energy systems to ensure maximum power point tracking, improving performance and efficiency, and enhancing the ability of solar systems to operate in various conditions. FSMC is a modern technology that enhances the efficiency of renewable energy systems.

Through intelligent control and dynamic adjustment, this method makes it possible to optimize the overall performance of solar systems, making it an ideal option for making the most of renewable energy.

This study's main goals were to build and execute a controller that uses FSMC and a variety of characteristics to solve a variety of issues in order to monitor the maximum power point. Secondly, it aimed to compare how well the controllers harvest solar energy. We were able to accomplish these objectives by means of thorough assessment and analysis.

Our research's objective was to close the gap in a thorough comparative study between conventional and contemporary MPPT algorithms and new technologies in order to offer insightful information to researchers, decision-makers, and solar customers.

By promoting the development of innovative solar energy technologies, our initiative aids in the worldwide shift to sustainable energy sources and facilitates efforts to mitigate climate change.

This paper presents a single-phase structure of grid-connected photovoltaic systems and their modeling. After that, in order to find out how it behaves on our proposed structure, we ran four commands to track the maximum power point through simulation in the Matlab/Simulink environment.

The results also showed that our structure has strong control over voltage, current, and active/reactive power input into the network.

This proposed strategy provides a practical way to manage photovoltaic power plants. Ultimately, this work can be improved and ideas can be drawn from it.

The proposed approach provides a feasible way to control photovoltaic systems. Improvements include improved energy storage and battery charge estimation of the stator transformer control loops.

A new maximum power point tracker called FSMC has created an adaptive fuzzy slide mode controller, which is based on a powerful high technique sliding mode. We first simulated this system using the Matlab/Simulink emulator.

To improve the performance of SMC and get rid of the chattering phenomenon, we have combined the adaptive fuzzy approach with the latter phenomenon. To check this console, we compared this approach with SMC, P&O, and fuzzy logic. The effectiveness and durability of the method are proved by the results of the recovered energy.

For future work, our goal is to verify the effectiveness of this controller by practical application using DSpace card.

The results can be validated experimentally by using the DSpace card which makes it possible to represent the control part in hardware form in our case which is responsible for data learning and fuzzy inference functions.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process.

The authors declare that they did not use any generative AI or AI assisted technologies in the writing process and they take the full responsibility for the content of the publication

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- Khoukha Bouguerra, Samia Latreche carried out the control and the implementation of the Algorithm.
- Mabrouk Khemliche and Hamza Khemliche have organized and performed the paper.

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Conflict of Interest

The authors have no conflicts of interest to declare.