Comparative Performance Analysis of Fuzzy Logic and PSO MPPT Controllers for Photovoltaic Systems

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Abstract. Photovoltaic energy plays a key role in reducing greenhouse gas emissions and tackling climate change. A crucial part of maximizing the energy output of photovoltaic systems is effective maximum power point tracking (MPPT). The control strategy used for MPPT not only affects the system's performance but also determines how well it can handle disturbances, making it essential for long-term efficiency. This study looks at two advanced control methods for photovoltaic systems: fuzzy logic (FL) and particle swarm optimization (PSO). Fuzzy logic proves to be quick, accurate, and reliable, even when sunlight levels change rapidly. In comparison, PSO is precise over time but struggles with slower adjustments, leading to short-term energy losses during sudden changes in sunlight.

Keywords. Photovoltaic energy (PV), Maximum Power Point Traking (MPPT), Particle Swarm Optimization (PSO), Fuzzy Logic (FL)

1 Introduction

PV system, commonly referred to as solar panels, are crucial to producing renewable energy. Their effectiveness depends on a procedure known as MPPT, which guarantees optimal performance. However, because it depends on factors like temperature and sunlight variations, this process is difficult to maintain. Researchers have developed several strategies to enhance MPPT over time. These include PSO and FL, both of which have shown promise in solving practical problems.

Inspired by human reasoning, fuzzy logic provides a flexible and dependable option for MPPT control because it is excellent at handling ambiguity and imprecise data. It works effectively in uncertain circumstances and is comparatively easy to deploy. Its accuracy and responsiveness, however, may be restricted, particularly when circumstances change quickly. PSO, on the other hand, provides a precise and flexible method for finding the optimal power point by drawing inspiration from natural swarm behavior, such as the movement of fish or birds. Even while PSO is typically more accurate and reliable, it might take longer to converge and requires more processing resources, especially in large-scale or complicated systems.

With an emphasis on accuracy, convergence speed, and overall resilience, this study attempts to assess and contrast these two MPPT techniques. Based on the unique needs and limitations of various applications, the objective is to ascertain which strategy provides the greatest fit for solar systems.

2 DESIGN AND MODELLING OF THE PROPOSED SYSTEM

Four key parts of a PV system combine to convert solar energy into electrical power that may be used. The first type is the PV panels, which use sunshine to generate electricity. The static DC-DC converter, specifically the Chopper Boost type, comes next. Through the adjustment of the impedance between the PV panels and the load, this component is essential for optimal energy extraction.

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Table 1. parameters of the photovoltaic system

Parameter	Label	Value
Switching frequency	f	5 KHz
Boost inductor	L	0,3 mH
Boost capacitor	C	342µF
Input capacitor	Cin	500µF
Load	R	60 Ω
Maximum Power	Pmax	620 Wp
Maximum Voltage	Vmp	45,79 V
Maximum Current	Imp	13,54 A
Open-circuit Voltage	Voc	55,55 V
Short-circuit Current	Isc	14,25 A
Number of panels	N	5

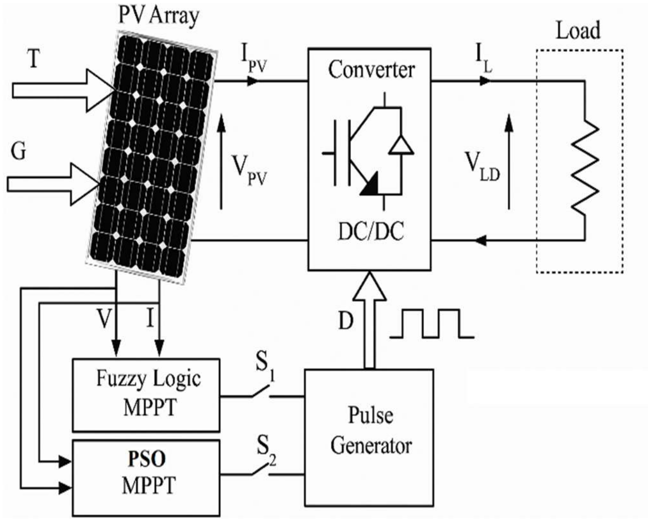


Fig. 1. Schematic diagram of the photovoltaic system

To guarantee optimal energy recovery even in the face of fluctuating solar conditions and system parameters, it controls voltage and current. The load, which stands for the energy demand, is the third element. Depending on the particular application or system needs, this demand may change. The control system is essential for monitoring and controlling how the overall system operates. It guarantees that the system functions effectively and maintains peak performance across all of its components by regularly monitoring the MPPT.

2.1 Design of the photovoltaic Panel

In order to manage and coordinate the system's overall operation, the control system is essential. It maintains optimal performance across all components and guarantees effective operation by continuously monitoring the MPPT.

$$I = I_{pv} - \left[I_0 e^{\left(\frac{V+R_S I}{\propto VT}\right)} - 1\right] - \frac{V+IR_S}{R_p} \tag{1}$$

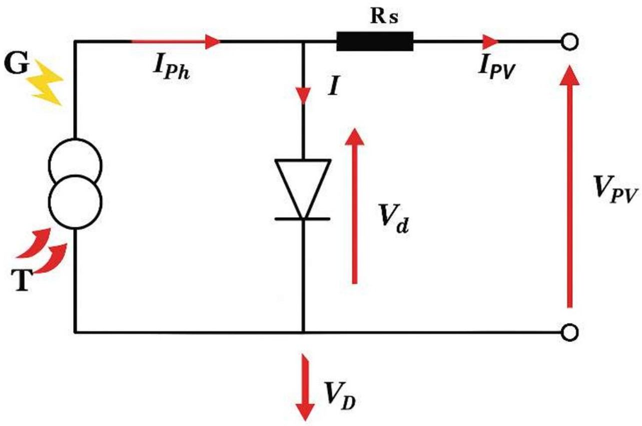


Fig. 2. Electrical equivalent circuit model of PV cell

Temperature and irradiance are the two main elements that affect photovoltaic panels' power production. Photovoltaic panels may produce their highest amount of power when the temperature is 25°C and the irradiation is 1000 W/m². But these norms are rarely exactly met in the real world. When the temperature is held constant at 25°C, variations in irradiance have a direct effect on the panel's current. As irradiance increases, the current and overall power output also rise proportionally. This relationship can be observed through the I-V and P-V characteristic curves of the "Tiger Neo N-type 78HL4-(V)" photovoltaic panel, which has a rated power of 620 W. These curves effectively illustrate how changes in sunlight and temperature conditions influence the panel's performance.

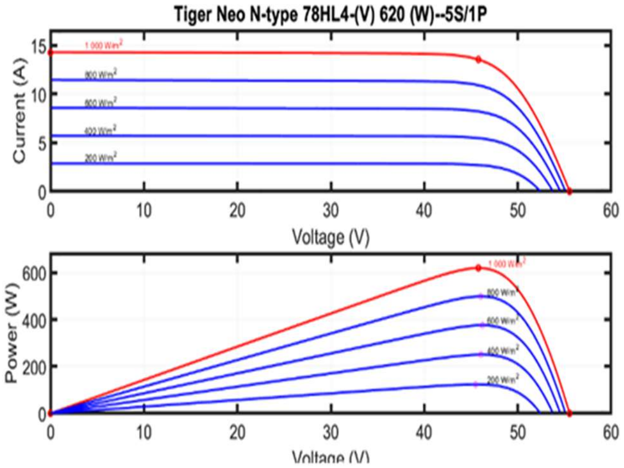


Fig. 3. Characteristic curves f(V)=I and f(V)=P with variation of irradiance E and T=25∘C

Temperature has a big impact on a solar panel's voltage output. Even when irradiance levels stay constant, higher temperatures result in a decline in voltage, which lowers total power generation. Since voltage and current both affect power output, lower temperatures result in higher voltage and more power being produced.
Maintaining lower operating temperatures can increase energy efficiency, which emphasizes the crucial role thermal management plays in photovoltaic systems. These temperature-dependent effects on panel performance are evident from the I-V and P-V characteristic curves of the "Tiger Neo N-type 78HL4-(V)" panel, which were recorded at different temperatures and with constant irradiation.

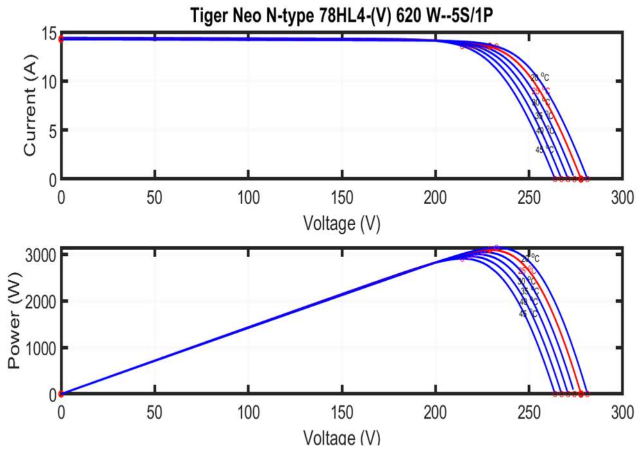


Fig. 4. Characteristic curves f(V)=I and f(V)=P with variation of temperature T and E=1000 W/ m²

2.2 Design of the Static Converter (BOOST Converter)

The boost converter, a crucial component of PV systems, regulates the voltage between the solar panel and the load. Its primary purpose is to increase the photovoltaic panel's output voltage when it falls below the optimal range, allowing the system to maximize the power it can supply. This is particularly important when the generated voltage is insufficient to meet the load's demands. When paired with a MPPT algorithm, the boost converter dynamically adjusts voltage and current in response to variations in temperature and sunshine. By maximizing energy extraction and ensuring steady performance even in the face of shifting external conditions, this combination makes sure the system runs constantly at its highest efficiency.
To maximize the amount of solar energy that can be extracted and guarantee optimal performance in a variety of conditions, this mechanism makes sure that the system always runs at its MPP. Kirchhoff's rules, which outline the electrical connections between the different converter parameters, provide the foundation of boost converter analysis. Equations relating the voltage at the converter's output (V_0ut), input voltage (V_in), output current (I_0ut), input current (I_in), and duty cycle (d) are established using these rules. The performance of the boost converter as a function of the input and output voltage and current levels, as well as the duty cycle that controls the converter's operation, may be ascertained using these relationships, which are represented in equations Eqs. 2 and 3. These formulas are necessary to comprehend and maximize the converter's performance in a photovoltaic system.

$$V_{0ut} = \frac{V_{in}}{(1-d)} \tag{2}$$

$$I_{in} = \frac{I_{out}}{(1-d)} \tag{3}$$

Input voltage and duty cycle are two key factors that significantly impact the efficiency of a boost converter. The converter's performance is optimized by adjusting these settings. The converter functions similarly to a voltage amplifier when the duty cycle reaches 100%, with the output voltage equal to the input voltage multiplied by a gain factor that is directly proportional to this ratio. Maximum voltage growth is possible with this mode of operation. Even though this operation appears to be the best way to maximize output voltage, non-ideal phenomena including conduction losses, switching losses, and the effect of the converter's internal resistance can cause efficiency losses. These non-ideal factors affect the overall efficiency of the system, even when the converter is set to operate at its maximum potential in terms of voltage conversion.

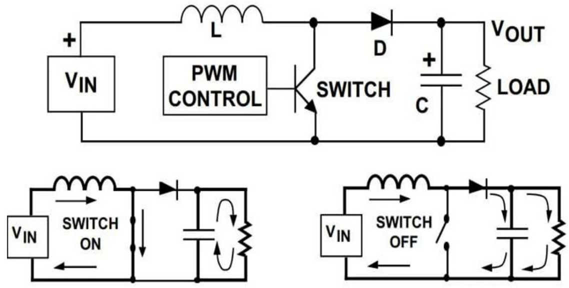


Fig. 5. The different states of the Boost converter

-Figure 5-a:

The transistor is in conduction (conducting) when t ∈ [0, αT]. Then, the following relationships can be used to characterize the converter's dynamic behavior:

$$\frac{dI_L}{dt} = \frac{V_1}{L} \quad (4)$$

$$\frac{dV_2}{dt} = -\frac{V_2}{RL_s} \quad (5)$$

-Figure 5-b:

For t ∈ [αT, T], the transistor is in the blocking state. The behavior of the converter can therefore be described by the following equations:

$$\frac{dI_L}{dt} = \frac{(V_1 - V_2)}{L} \quad (6)$$

$$\frac{dV_2}{dt} = \frac{I_L}{C_s} - \frac{V_2}{C_s R_L} \quad (7)$$

Where T is the period of the static converter, and α is the duty cycle, defining the fraction of the period during which the transistor is conducting.

2.3 MPPT control design

For a solar system to operate as efficiently as possible, MPPT control is a crucial component. Its foundation is the basic idea of dynamically varying the α duty cycle of the inverter. This dynamic adjustment maximizes the power collected from the photovoltaic panel by enabling real-time modulation of the duty cycle to attain its optimal value. This technique allows the system to adjust to changes in temperature and sunlight, maximizing the amount of solar energy that may be used. Because MPPT control maintains the system at the PPM continuously, it is crucial to the energy efficiency of solar installations.

The PSO algorithm and fuzzy logic are the two forms of MPPT control that are compared in this paper. This analysis's primary goal is to assess the effectiveness of these two control strategies while emphasizing each one's benefits and drawbacks. To ascertain which of these approaches best maximizes the extraction of MPP from the photovoltaic panel, this review attempts to comprehend how each system responds to various sunshine and temperature situations. To help choose the best technique for photovoltaic systems, the study aims to give a thorough review of the capabilities and efficiencies of these two techniques to tracking the point of greatest output.

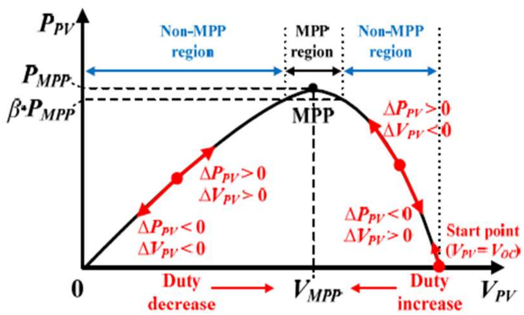


Fig. 6. Principle of operation for the MPPT algorithm

3 OVERVIEW OF THE DIFFERENT MPPT CONTROL TECHNIQUES

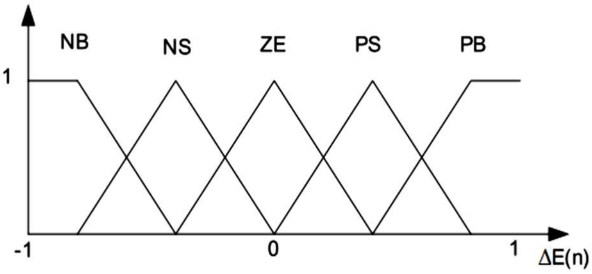


Fig. 7. Membership Functions of the Variable ΔE

3.2 Fuzzy logic control

A very powerful control method is fuzzy logic, especially for systems with unknowns or fluctuating parameters. It is perfect for applications such as MPPT in solar systems because it bridges the gap between classical logic and real-world imprecision. In this case, the DC-DC Boost converter's duty cycle is adjusted using fuzzy logic to maximize power extraction from the solar panel. Without requiring a comprehensive model, the fuzzy controller analyzes power error and its rate of change, converting these values into accurate changes for the best system performance.

3.2.1 Input fuzzification interface

The fuzzy controller's input physical quantities are transformed into linguistic variables by the fuzzification operation so that the inference mechanism can process them. Fuzzification transforms the numerical input variables into a language variable with five possible values:

- NB: Negative Big,
- NS: Negative Small,
- ZE: Zero,
- PS: Positive Small,
- PB: Positive Big.

The fuzzy control has two inputs, namely the error E(k) and the variation of the error ΔE(k) expressed by:

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

$$\Delta E = E(K) - E(K-1) \quad (9)$$

Such as:

$$P(K) = I(K) * V(K) \quad (10)$$

The direction of movement of this point is expressed by the value ΔE. Inference in our study is done using Mamdani's approach.

$$D = \frac{\sum_{j=1}^{n} \mu(D_j) - D_j}{\sum_{j=1}^{n} \mu(D_j)} \quad (11)$$

With:

- P_pv and V_pv are the power and voltage of the photovoltaic generator respectively.
- E(k): the first input indicates whether the load operating point is to the left or right of the maximum power point on the P-V curve.
- ΔE: the second input shows the direction of the operating point.

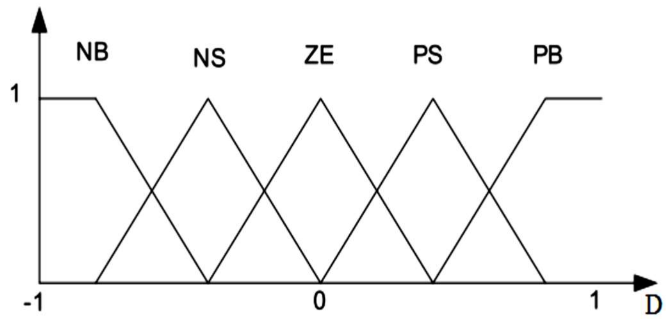


Fig. 8. Membership Functions of the Variable ΔD

- μ(D_j) : Membership functions
- D: The output of the fuzzy controller is which represents the variation in the duty cycle of the DC-DC converter. The subsequent figures illustrate the membership functions of the five fuzzy subsets about the input parameters and the output factor.

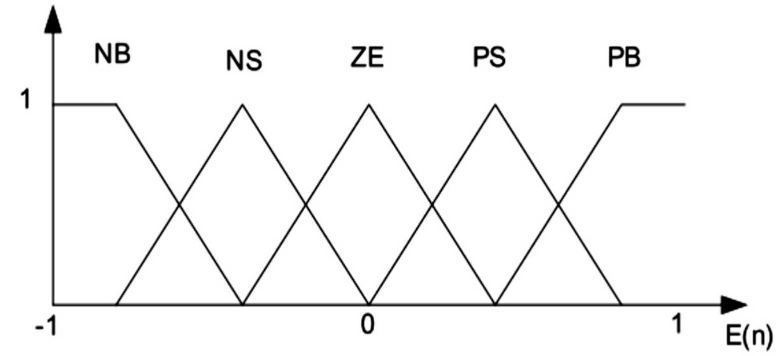


Fig. 9. Membership Functions of the Variable E

3.2.2 Rules

The system uses a set of fuzzy rules to deduce a decision from the fuzzy values of the inputs. An inference is then made on the basis of a set of rules displayed in the subsequent table.

Table 2. The Rule Base for Fuzzy Control

E/ΔE	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

3.2.3 Defuzzification

Defuzzification is a crucial stage in fuzzy control of a PV system, transforming the fuzzy controller's judgments into tangible actions that have an impact on the system. A fuzzy controller is frequently used to maximize the power collected from a solar panel under changing temperature and sunlight conditions. This is especially true when MPPT control is involved. In defuzzification, membership functions are used to convert the resulting fuzzy output into an output that the external environment can read.

3.3 The PSO algorithm

A bio-inspired optimization method called particle swarm optimization (PSO) imitates group behaviors found in nature, including fish or bird migration. It makes use of a swarm of particles, each of which represents a possible solution. The particles iteratively update their positions according to two factors: the swarm's discovery of the global best position (G_best) and their own best position (P_best). As a result, the swarm can converge on an ideal or nearly ideal solution. PSO works especially well in situations when conventional approaches might not be able to handle complicated, non-linear issues with big search spaces. Important parameters that affect the algorithm's performance are swarm size, acceleration coefficients, and inertia weight. The algorithm's convergence efficiency is also greatly influenced by the communication topology, which specifies how particles exchange information. The particles' movements are guided by the update equations at the core of PSO, which strike a balance between search space exploration and exploitation while steering clear of local optima. The following equations can be used to formalize the process by expressing the updates of the particle locations and velocities:

3.3.1 Speed update :

$$v_i(t+1) = w * v_i(t) + c_1 * r_1 * \left(P_{besti} - x_i(t)\right) + c_2 * r_2 * \left(G_{besti} - x_i(t)\right) \quad (12)$$

3.3.2 Position update:

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (13)$$

Where:

- $v_i(t)$ represents the velocity of particle i at time t,
- $x_i(t)$ represents the position of particle i at time t,
- P_{best} is the best position found by particle i,
- G_{best} is the best position found by the population as a whole,
- c_1 c_2 are the acceleration factors that control the influence of P_{best} and G_{best},
- r_1 r_2 are random numbers between 0 and 1,
- w is the inertia factor which controls the influence of the previous speed.

The PSO algorithm is frequently used in photovoltaic systems, especially for MPPT management, where it maximizes solar panel energy extraction and raises system efficiency. Its capacity to adjust to changing environmental factors, such temperature and irradiance, enables the best possible energy harvest under dynamic and uncertain circumstances. The performance and dependability of contemporary solar systems are improved by this versatility.

4 SIMULATION RESULTS

In this work, the simulation results are divided into two sections:

- Section A: E=1000 W/m² and T=25°C
- Section B: T=25°C and variable E

Optimizing MPPT control performance in a solar system under constant temperature (T = 25°C) and irradiance (E = 1000 W/m2) is the goal of this work. It evaluates how well two sophisticated control techniques— FL and PSO—improve MPPT while taking temperature and irradiation variations into account. The objective is to determine which approach performs best for photovoltaic systems in terms of reactivity, stability, and optimal yield. Each control approach is color-coded in the graphs that visually represent the findings. While the y-axis displays measured physical quantities like electrical power, current, or voltage, the x-axis displays time.

4.1 Section A: E=1000 W/m² and T=25°C

This section examines the system's performance under constant irradiation conditions of 1000 W/m² and ambient temperature conditions of 25°C. The power, current, and voltage curves at the load terminals are displayed in the results:

- Power: Maximum power values are reached at a certain optimum operating point.
- Current: Current is directly proportional to illuminance and collector surface area.
- Voltage: Voltage varies according to lighting conditions and any losses in the system.

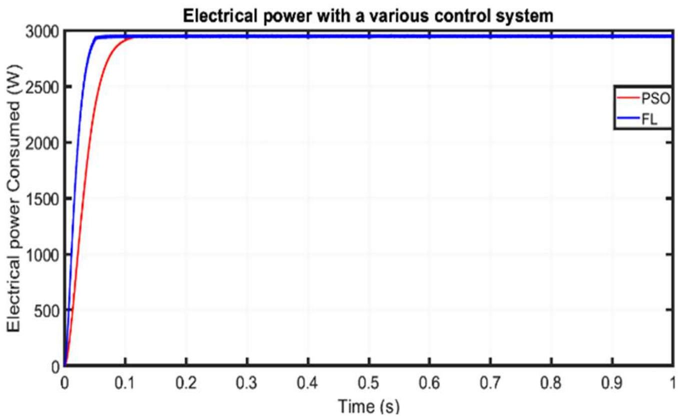


Fig. 10. Electrical power curve with a various system

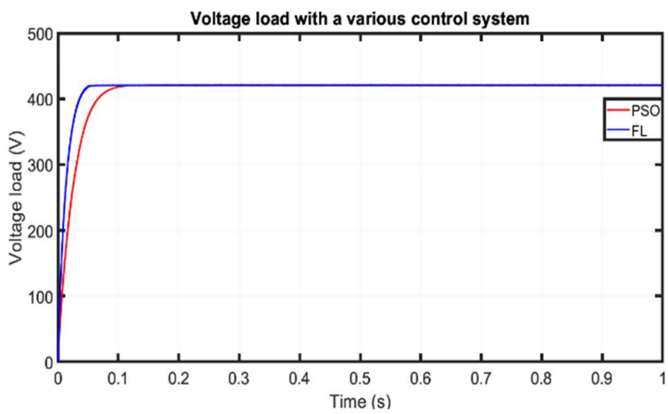


Fig. 11. Voltage load curve with a various system

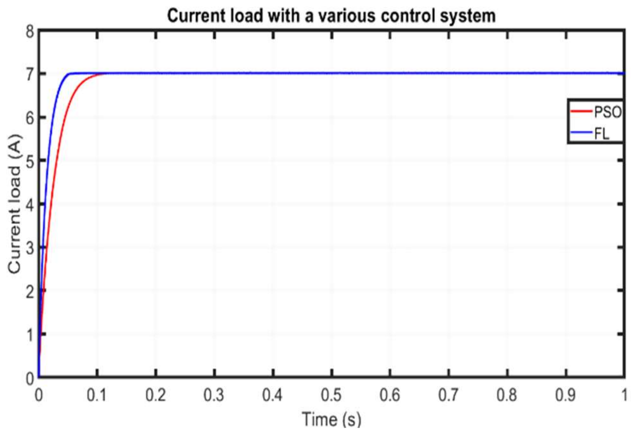


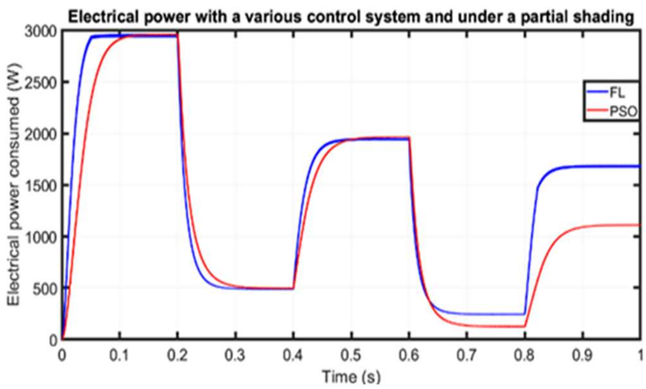
Fig. 12. Current load curve with a various system

The simulation figures above show that the photovoltaic system is converging towards the optimum values.

4.2 Section B: T=25°C and variable E

In this section, we examined how well the system performed when the temperature remained at 25°C and the amount of sunshine varied. With this method, we may evaluate how resilient the system is to variations in solar radiation. We can assess how well the algorithm optimizes power extraction while ensuring system stability in the face of external disturbances, like abrupt changes in temperature or irradiation, by examining how the power consumed and the electrical parameters (voltage and current) at the load terminals respond to these variations in solar irradiation.

- Power: Variations in power as a function of illuminance show peaks at specific irradiation levels.
- Current: The current curve shows a rapid response to changes in illumination.
- Voltage: Voltage varies non-linearly, influenced by lighting conditions.



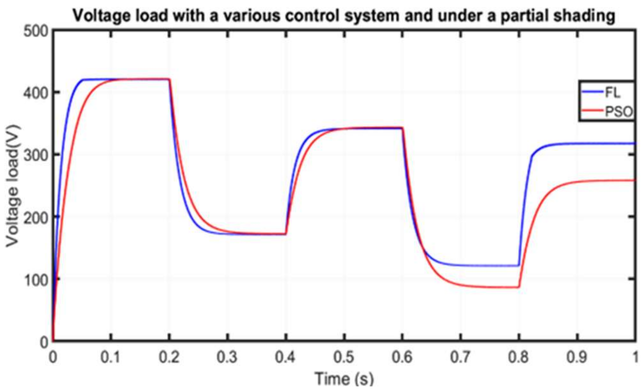


Fig. 13. Electrical Power curve with a various control system and under a partial shading

Fig. 14. Voltage Load with a various control system and under a partial shading

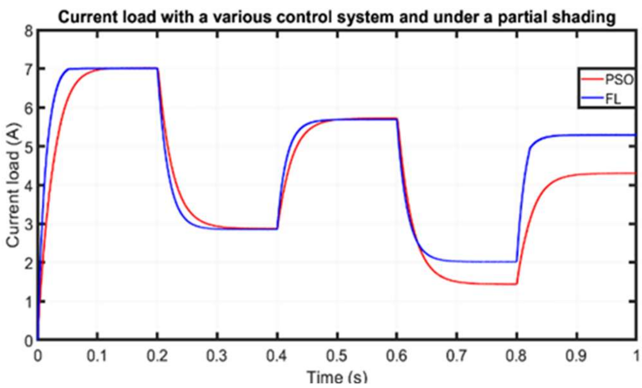


Fig. 15. Current Load with a various control system and under a partial shading

Figures showing how the performance of a PV system changes in response to changes in solar irradiation at a temperature of 25°C with MPPT control applied by various control types, including intelligent, hybrid, and conventional.

5 DISCUSSION

Two different situations were used for the simulations: variable E with T = 25°C and E = 1000 W/m². The objective is to evaluate the stability, responsiveness, efficiency, and resilience to irradiation disruptions of the two MPPT control techniques, namely FL and PSO.

Table 3. Performance indices for a various control system

	Fuzzy Logic	**PSO**
Rise Time (10%) in ms	29,9	56,5
Response Time (5%) in ms	41	78
IAE	130	148,2
ITAE	31,2	24,99
ISE	1,516	2,077
Efficiency MPPT	99,04%	96,98%

Table 4. Qualitative Performance for divers control systems

Criteria	**FL Control**	**PSO Control**
Reactivity	Very reactive, immediate adjustment to conditions.	Less rectivity, requires optimization iterations.
Precision	Less precise than PSO.	More precise, seeks a global optimum.
Complexity	Simple to implement.	More complex, requires more resources.
Robustness	Very robust against disturbances.	Robust but less responsive to sudden disturbances.
Response Time	Very fast, suitable for rapid changes.	Slower due to optimization by iterations.
Resource Consumption	Low resource consumption.	Consumes more resources for optimization.
Adaptability	Highly adaptable in real-time.	Less adaptable to rapid changes.
Cost	Less expensive to implement.	More expensive in terms of computation and implementation.

4.3 Section A: E = 1000 W/m², T = 25°C

4.3.1 Fuzzy control (FL)

In this instance, the solar system can swiftly reach MPP thanks to FL. The system maintains high stability and consistently follows the MPP with few oscillations because of its dynamic control principles. The fact that there are no oscillations around the MPP indicates that fuzzy logic guarantees precise MPP tracking, maximizing power output while minimizing losses.

- Response speed: Very fast, with reduced rise time.
- Stability: Excellent stability with precise MPP tracking and no oscillations.
- Efficiency: Maximization of power extraction with very precise regulation.

4.3.2 Particle Swarm Optimisation

Although PSO takes longer to converge than LF, it too demonstrates a strong potential to reach MPP. This is because the PSO technique is iterative, requiring multiple iterations to optimize the parameters and get maximum power.

- Response speed: slower than LF, due to the iterative search for the optimum.
- Stability: The system also reaches the MPP accurately, but takes longer to do so.

- Performance: After convergence, performance is similar to that of FL, but the initial transition takes longer.

4.3.3 Synthesis

- Reactivity: Fuzzy logic is more reactive and reaches the MPP more quickly, offering almost instantaneous monitoring with minimal losses. On the other hand, PSO is slower to converge towards the MPP.
- Stability: Both strategies show high stability, but fuzzy logic maintains a more stable and immediate MPP tracking.
- Performance: The return is comparable for both methods in the long term, but fuzzy logic allows faster optimal exploitation.

4.4 Section B: T = 25°C, E variable

4.4.1 Fuzzy control

FL instantly adapts to the new circumstances when irradiance changes (for instance, because of clouds or other disruptions). The system's adaptive rules allow it to continuously and dynamically modify the parameters, guaranteeing precise and steady MPP monitoring. By minimizing variances around the MPP, fuzzy logic offers a quick reaction to irradiation changes.

- Response speed: Very fast, with immediate reactivity to irradiation variations.
- Stability: High stability, even in the event of rapid irradiation fluctuations.
- Efficiency: Very high, as the system remains close to MPP throughout the period of irradiation variation.

4.4.2 Particle Swarm Optimisation (PSO)

Although PSO is effective in finding the global maximum power, it takes longer to readjust the system in the face of a variation in irradiation. The algorithm has to perform several iterations before finding a new optimal MPP, which reduces stability and prolongs response time. During this adaptation period, the system may lose performance, leading to a temporary reduction in energy efficiency.

- Response speed: Less reactive than LF, with a longer adaptation time.
- Stability: Stability is less well maintained during the adjustment period, which can lead to small fluctuations around the MPP.
- Performance: Overall performance remains good, but the adjustment period leads to a temporary reduction in efficiency.

4.4.3 Synthesis

- Reactivity: Fuzzy logic (FL) offers a much faster response to variations in irradiation, with almost immediate adjustment of the parameters. PSO, on the other hand, takes several iterations to adjust its parameters, resulting in a delay in response.
- Stability: Fuzzy logic maintains higher stability, by adjusting its parameters in real time to follow the MPP. PSO suffers from a longer transient period during which stability is less optimal.
- Performance: Because of its ability to react instantaneously, fuzzy logic provides a more stable and constant performance under variable irradiation conditions. PSO, while performing well in the long term, suffers from performance losses during initial adaptation to irradiation variations.

Accuracy, convergence speed, and system stability are evaluated using performance indices including Integral Square Error (ISE), Integral Absolute Error (IAE), and Integration Time Weighted Absolute Error (ITAE) in MPPT control techniques. When FL and PSO are compared, FL performs better than PSO in terms of accuracy, stability, and faster convergence. FL tracks the maximum power point (MPP) more steadily and quickly under a variety of scenarios thanks to its reduced performance indices. PSO, on the other hand, has larger indices, indicating slower convergence and transient efficiency losses during abrupt changes in irradiance, despite its long-term effectiveness. Thus, FL is better suitable for systems that need to adjust quickly, whereas PSO might be taken into account for settings that are more stable.

6 CONCLUSION

By optimizing power extraction in a variety of environmental situations, MPPT control is crucial for improving the performance of solar systems. In dynamic situations with rapid irradiance variations, fuzzy logic (FL) is very useful because to its fast response, excellent maximum power point (MPP) tracking, and stability in both constant and variable irradiation conditions. Particle Swarm Optimization (PSO), on the other hand, provides good long-term outcomes but has longer convergence times, which causes short-term yield losses during abrupt changes in irradiation. FL exhibits benefits over PSO, such as a 3% increase in system efficiency and a 47% improvement in rise and reaction times. As a result, FL is recommended for systems that need to be stable and responsive quickly, especially when exposed to varying levels of radiation.

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