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Improved Maximum Power Point Tracking in Photovoltaic Systems via Fuzzy Backstepping Sliding Mode Control and PSO Optimization

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Abstract: This paper presents a novel maximum power point tracking (MPPT) control strategy for photovoltaic (PV) systems that integrates fuzzy logic with backstepping sliding mode control (FBSMC), optimized via particle swarm optimization (PSO). The proposed FBSMC approach addresses the nonlinear and dynamic nature of PV systems under varying environmental conditions such as fluctuating irradiance, temperature variations, and partial shading. By embedding fuzzy logic into the backstepping sliding mode framework, the controller dynamically adjusts control parameters, significantly reducing chattering-a common drawback of traditional sliding mode control-while improving tracking accuracy and response speed. PSO is employed to systematically optimize the fuzzy controller parameters, thereby enhancing convergence speed and overall system performance without relying on heuristic tuning. Simulation results demonstrate that the FBSMC method outperforms conventional MPPT techniques such as Perturb and Observe (P&O) and standard sliding mode control in terms of power output, settling time, and mean squared error (MSE). The findings confirm that the proposed hybrid controller provides a robust, efficient, and reliable solution for real-world PV applications, facilitating optimal power extraction and contributing to the broader adoption of renewable energy technologies.

Keywords*: Fuzzy Logic Control, Particle Swarm Optimization, Maximum Power Point Tracking, Sliding Mode Control, PV Systems.*

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I. INTRODUCTION

The escalating global demand for clean and renewable energy sources has intensified interest in solar power as a viable alternative to conventional fossil fuels. Solar energy, abundant and environmentally friendly, offers a sustainable solution to mitigate the depletion of finite fossil fuel reserves and reduce greenhouse gas emissions. Despite its potential, efficiently harnessing solar energy through photovoltaic (PV) systems remains challenging due to the inherent variability of environmental conditions, such as fluctuating solar irradiance and temperature changes, which significantly impact the power output of solar panels.

To maximize the energy harvested from PV systems, Maximum Power Point Tracking (MPPT) techniques have been widely developed and implemented. MPPT algorithms dynamically adjust the operating point of the PV system to ensure it functions at the Maximum Power Point (MPP), where power output is maximized. This task is complicated by the nonlinear current-voltage (I-V) characteristics of PV modules, which vary with environmental factors such as temperature and irradiance. Consequently, effective MPPT methods are critical for optimizing the energy yield from solar panels under diverse and rapidly changing conditions.

Several MPPT techniques have been proposed, including the widely used Perturb and Observe (P&O), Incremental Conductance (INC), and Sliding Mode Control (SMC). While these traditional methods have demonstrated effectiveness, they often face limitations such as slow convergence, oscillations around the MPP, and difficulty adapting to fast environmental changes. Among these, SMC has gained prominence due to its robustness in handling nonlinear systems like PV modules, offering fast response and disturbance rejection capabilities. However, a significant drawback of conventional SMC is the phenomenon of chattering-high-frequency oscillations around the MPP caused by the discontinuous switching control signal. Chattering not only reduces power extraction

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efficiency but may also lead to mechanical wear and system instability.

To overcome these challenges, advanced variants of SMC have been explored. Backstepping Sliding Mode Control (BSMC) is one such approach that employs a recursive design methodology grounded in Lyapunov stability theory, enhancing system stability and tracking performance. Despite these improvements, BSMC still suffers from chattering, particularly under rapidly fluctuating environmental conditions. Integrating fuzzy logic control (FLC) with BSMC presents a promising solution. FLC excels in managing nonlinear systems with uncertain or imprecise inputs by mimicking human reasoning, thus enabling smoother control actions. By replacing the discontinuous switching function in SMC with fuzzy logic, the resulting Fuzzy Backstepping Sliding Mode Control (FBSMC) can significantly reduce chattering while maintaining robustness and adaptability to changing conditions. This hybrid approach facilitates smoother transitions to the MPP and enhances overall system performance.

Nevertheless, tuning the fuzzy controller parameters remains a challenging and often heuristic process. To address this, optimization algorithms such as Particle Swarm Optimization (PSO) have been employed. PSO, inspired by the collective behavior of social organisms, efficiently searches the parameter space to identify optimal or near-optimal solutions, improving controller performance without exhaustive manual tuning. Applying PSO to optimize the fuzzy controller within the FBSMC framework ensures faster convergence, better tracking accuracy, and enhanced robustness.

The significance of efficient MPPT cannot be overstated, as even marginal improvements in tracking precision translate into substantial gains in energy harvesting efficiency. Rapid adaptation to environmental changes is essential for maximizing power extraction and ensuring the economic viability of PV systems. As solar energy continues to expand its role in the global energy portfolio, the development of advanced, reliable, and computationally efficient MPPT algorithms is increasingly critical.

This research proposes a novel MPPT controller that integrates fuzzy logic with backstepping sliding mode control, further optimized by PSO. The objective is to design a control system that eliminates chattering, accelerates convergence to the MPP, and maintains high tracking accuracy under dynamic conditions such as partial shading, rapid irradiance fluctuations, and temperature variations. The proposed hybrid controller is evaluated through comprehensive simulations replicating real-world PV operating scenarios, demonstrating its superior performance compared to conventional MPPT techniques.

II. RELATED WORKS

Recent years have seen significant advancements in maximum power point tracking (MPPT) techniques for photovoltaic (PV) systems, driven by the need to improve energy conversion efficiency under dynamic environmental conditions. Numerous intelligent and hybrid control strategies have been proposed to address the nonlinear and time-varying characteristics of PV arrays, particularly under rapidly changing irradiance and temperature. Reinforcement learning-based MPPT methods have emerged as promising alternatives to conventional approaches. For example, Chou et al. introduced two Q-learning-based strategies-one using a Q-table and another leveraging a Q-network. These methods do not require prior knowledge of PV module characteristics and employ a two-phase offline training process. The Q-table approach reduces oscillations, while the Q-network achieves higher average power output, demonstrating the adaptability of reinforcement learning in MPPT applications. Fuzzy Logic Control (FLC) has also been widely adopted for MPPT due to its ability to handle system uncertainties and nonlinearities. Haddouche et al. proposed a simplified fuzzy rule set for MPPT, reducing the traditional 25-rule base to increase tracking speed and decrease static error, thereby improving overall system performance. Similarly, Babes et al. utilized a multilayer feed-forward artificial neural network (ANN) controller, optimized with ant colony optimization (ACO), for grid-connected PV systems. This approach resulted in faster and more reliable MPPT with minimal steady-state oscillations, particularly in larger-scale systems. Hybrid and optimization-based controllers have shown further improvements in tracking efficiency. Ullah et al. combined the Perturb & Observe (P&O) method with fuzzy logic, achieving system efficiencies up to 97% in simulation studies. Meanwhile, Ali et al. and Hameed et al. explored nonlinear sliding mode control (SMC) techniques integrated with P&O for enhanced power extraction. Their MATLAB simulations demonstrated that SMC-based MPPT offers faster response and reduced power losses compared to traditional PID controllers, with system stability ensured by Lyapunov theory.

To address the persistent issue of chattering in SMC, researchers have proposed several enhancements. For instance, a novel SMC structure with a multi-power reaching law and sigmoid function was introduced, improving robustness and efficiency over conventional SMC. Delavari et al. developed an indirect adaptive fuzzy fractional-order SMC, which uses an adaptive fuzzy system to estimate unknown dynamics and maintain stability despite disturbances. Adouairi et al. combined fuzzy logic with SMC to control inverter input voltage for MPPT, achieving strong performance without the need for a DC-DC converter, thus reducing system complexity and cost. Backstepping and neural network-based approaches have also gained traction. Behih et al. implemented backstepping terminal SMC (BTSMC) for MPPT, demonstrating improved efficiency and Lyapunov-guaranteed stability. Khan et al. used a radial basis function neural network (RBF NN) to generate reference voltages, achieving 98.74% efficiency with BTSMC. Lamzouri et al. enhanced BSMC

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with integral action and optimized its performance using particle swarm optimization (PSO), significantly minimizing tracking errors. Harrison et al. integrated an artificial neural network and backstepping controller for reference prediction, outperforming traditional MPPT methods. Al-Wesabi et al. combined the Salp Swarm Algorithm (SSA) with PSO and intelligent direct SMC to stabilize DC-bus voltage and reduce ripples, ensuring reliable power output under fluctuating conditions.

➢ *Summary and Research Gap:*

While these advanced MPPT strategies-including reinforcement learning, fuzzy logic, neural networks, and optimized SMC variants-have demonstrated improvements in tracking accuracy, efficiency, and robustness, several challenges remain. Many approaches add complexity or computational burden, and issues such as chattering, adaptability to rapidly changing conditions, and the need for real-world validation persist. In particular, the integration of fuzzy logic with backstepping SMC, further refined with optimization algorithms like PSO, offers a promising direction for achieving robust, adaptive, and computationally efficient MPPT control. However, there is still a need for hybrid controllers that can minimize chattering, maintain high tracking accuracy, and operate reliably under diverse and unpredictable environmental scenarios.

III. PROPOSED METHODOLOGY

This section presents the methodology aimed at improving the efficiency and stability of MPPT in PV systems. This approach combines Fuzzy Logic with BSMC, further optimized using PSO to reduce chattering and boost system performance under varying environmental conditions. The goal of this hybrid control strategy is to achieve faster convergence to the MPP while maintaining resilience against sudden changes in irradiance and temperature. The following subsections outline the structure of the PV system, the development of the control algorithm, and the optimization process used to fine-tune the controller parameters for optimal performance.

A. Photovoltaic System Model

In this subsection, we introduce the mathematical model of the PV system, highlighting the I-V characteristics and the role of the DC-DC converter in regulating output. The architecture of basic PV system is shown in Figure 1. A PV cell, the fundamental unit of a PV module, generates electricity when exposed to sunlight. The output current (I_{PV}) from a PV cell is a function of the generated current (I_{gen}) and the diode saturation current (I_{sat}), which follows the Shockley diode equation. This relationship can be mathematically expressed in Eq. 1.

$$I_{PV} = I_{gen} - I_{sat}\left(e^{\frac{V_{PV}+I_{PV}R_S}{nV_t}} - 1\right) \quad \text{Eq. (1)}$$

V_t is the thermal voltage, given by $V_t = \frac{kT}{q}$, where k is the Boltzmann constant, T is the cell temperature, and q is the charge of an electron. The generated current I_{gen} depends on the solar irradiance (G) and temperature (T) and can be approximated as in Eq. 2.

$$I_{gen} = G \cdot \left(I_{SC} + K_I(T - T_{\text{ref}})\right) \quad \text{Eq. (2)}$$

The short-circuit current (I_{SC}) represents the current produced when the PV cell is exposed to sunlight under ideal conditions with no load. It is influenced by the temperature, with the temperature coefficient (K_I) indicating how much the short-circuit current changes with variations in temperature. The reference temperature (T_{ref}) corresponds to the standard test conditions used to evaluate the performance of the PV cell. These factors collectively establish the connection between the current output and the PV system's operating conditions.

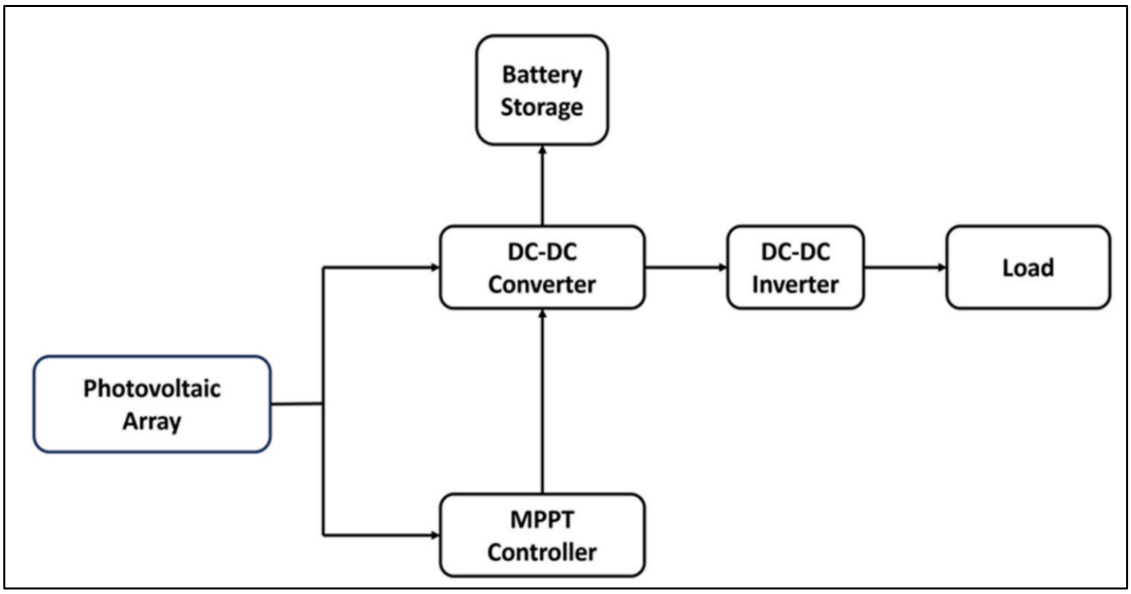

Fig 1. Architecture of Basic PV System

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To optimize power extraction, a DC-DC converter is commonly used in a PV system. The DC-DC boost converter adjusts the PV module's output voltage to ensure the system operates close to its MPP. The input-output relationship of the boost converter is managed by adjusting the duty cycle (D), which controls the output voltage (V_{out}). This allows the converter to maintain optimal performance and maximize the power generated by the PV system. The output voltage can be controlled as in Eq. 3.

$$V_{out} = \frac{V_{PV}}{1-D} \qquad \text{Eq. (3)}$$

In this model, the DC-DC converter continuously adjusts the D, enabling the MPPT controller to regulate the voltage and ensure that the PV system consistently operates at its optimal point for maximum power extraction. The interaction between the I-V characteristics of the PV module and the control provided by the DC-DC converter forms the basis for the control strategies discussed in this paper.

B. Backstepping Sliding Mode Control (BSMC)

BSMC is an advanced technique aimed at improving the stability and efficiency of MPPT in photovoltaic systems. Its key strength lies in its ability to handle the non-linear behavior of PV systems, providing robust control even under changing environmental conditions, such as fluctuating sunlight and temperature. This control strategy employs a step-by-step design process that ensures system stability by applying Lyapunov-based stability principles.

In this approach, the controller's main goal is to adjust the D of the “DC-DC boost converter” to regulate the V_{PV}, ensuring it follows the V_{ref} corresponding to the MPP. The system stays near the MPP by continuously fine-tuning the duty cycle. The tracking error, defined as $e_1 = V_{ref} - V_{PV}$, guides the control process. To enhance stability and control precision, another error term, $e_2 = \dot{e}_1 + K_1 e_1$, is introduced, further refining the system's performance. The sliding surface S, which serves as the core of the SMC, is defined in Eq. 4:

$$S = e_2 - k_2 e_1 = (K_1 - K_2)e_1 + \dot{e}_1 \qquad \text{Eq. (4)}$$

The controller is designed to keep the system's behaviour on this sliding surface, which gradually reduces the tracking error to zero, ensuring maximum power extraction. The control input $u_{BSMC}(t)$ consists of two components; The control input $u_{eq}(t)$ represents the equivalent control, which is responsible for guiding the system to follow the desired behavior and dynamics. On the other hand, $u_{co}(t)$ serves as the corrective control, working to address and eliminate any errors that may arise due to external disturbances or uncertainties in the system model. Together, these two components ensure precise and stable system performance. The expressions for $u_{eq}(t)$ and $u_{co}(t)$ are given as in Eq. 6 and 7.

$$u_{BSMC}(t) = u_{eq}(t) + u_{co}(t) \qquad \text{Eq. (5)}$$

$$u_{eq}(t) = \frac{-V_{PV} + \dot{I}_{PV} - C_1 \dot{V}_{ref} + C_1(K_2 - K_1)e_1}{gL} \qquad \text{Eq. (6)}$$

$$u_{co}(t) = \frac{-C_1 a(S + b \cdot \mathrm{sgn}(S))}{gL} \qquad \text{Eq. (7)}$$

In sliding mode control, the sign function, represented as $\mathrm{sgn}(S)$, is used to dictate the switching behavior of the controller. However, this function can result in abrupt switching, which often leads to an undesirable effect known as chattering. The constants a and b are carefully designed parameters that help shape the control law, while gL represents the system gain, which influences the overall response and performance of the control system. The sliding surface dynamics are represented by Eq. 8.

$$\dot{S} = -a(S + b \cdot \mathrm{sgn}(S)) \qquad \text{Eq. (8)}$$

This approach make sure that the system remains on the sliding surface throughout its operation. To guarantee asymptotic stability, a Lyapunov function is chosen, and its derivative must be negative. This condition ensures that the tracking error decreases over time, guiding the system towards stability. The Lyapunov function is mathematically defined in Eq. 9. Using Barbalat’s lemma for asymptotic stability, the conditions in Eq. 10 satisfied:

$$V_{typ} = V_1 + \frac{S^2}{2} = \frac{e_1^2 + S^2}{2} \qquad \text{Eq. (9)}$$

$$\left.\begin{array}{r} a > 0 \\ b > 0 \\ K_1 > 0 \\ h(K_1 - K_2) > \frac{1}{4} \end{array}\right\} \qquad \text{Eq. (10)}$$

In this approach, the parameters K_1, K_2, a, and b are carefully chosen to guarantee the stability of the closed-loop system. By utilizing a recursive design grounded in Lyapunov stability principles, this approach ensures that the BSMC effectively steers the PV system to operate at the MPP with minimal error, while consistently delivering high performance even in the face of external disturbances and fluctuating environmental conditions.

C. Fuzzy Logic Integration

To improve the performance of the BSMC and mitigate the chattering issue often found in traditional sliding mode control, fuzzy logic is incorporated into the control strategy. Chattering, which results from the high frequency switching of the control signal, can cause inefficiencies in the PV system and lead to mechanical wear in real-world applications. By integrating fuzzy logic, which is effective at managing non-linearities and uncertainties, the

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discontinuous sign function (sgn(S)) in the SMC is replaced, allowing for smoother control transitions and significantly reducing chattering.

In this hybrid approach, the FLC generates smooth control actions by analysing changes in the PV system's voltage and power. It operates using a set of fuzzy rules based on expert knowledge, allowing it to effectively manage complex dynamic systems without requiring an exact mathematical model. The inputs to the fuzzy controller are the variations in voltage (ΔV_{PV}) and power (ΔP_{PV}), enabling the system to adapt efficiently to changing conditions. The voltage variation, ΔV_{PV}, refers to the difference in the output voltage between two consecutive time steps, reflecting how the voltage changes over time. Similarly, the power variation, ΔP_{PV}, represents the change in power output during the same time interval. These variations provide important feedback to the FLC, enabling it to make real-time adjustments to optimize the system's performance.

$$\Delta V_{PV} = V_{PV}(t) - V_{PV}(t-1)$$
Eq. (11)

$$\Delta P_{PV} = P_{PV}(t) - P_{PV}(t-1)$$
Eq. (12)

These two variations, voltage and power, are used as inputs for the FLC because they directly impact the MPP tracking performance. The controller interprets these changes to adjust the duty cycle of the DC-DC converter, helping the system move towards the MPP with minimal oscillations and smoother transitions. The output of the FLC, represented as d_{fuzzy}, replaces the traditional discontinuous sign function (sgn(S)) in the BSMC control law. This results in an updated control input for the fuzzy-based BSMC, ensuring more refined and efficient system control.

$$u_{FBSMC}(t) = u_{eq}(t) + \frac{-C_1 a(S + b \cdot d_{fuzzy})}{gL}$$
Eq. (13)

The fuzzy logic controller functions using a set of if-then rules, Eq. 14, which generate the output based on the inputs ΔV_{PV} and ΔP_{PV}. These rules are derived from the relationship between changes in voltage and power, guiding the controller to adjust the system's behavior for more efficient tracking of the MPP.

$$\begin{Bmatrix} \textbf{\textit{If}}\ \Delta V_{PV}\ \textit{is}\ \textbf{\textit{positive}}\ \textit{and}\ \Delta P_{PV}\ \textit{is}\ \textbf{\textit{positive}}, \textbf{\textit{then}}\ d_{fuzzy}\ \textit{is}\ \textbf{\textit{positive medium}} \\ \textbf{\textit{If}}\ \Delta V_{PV}\ \textit{is}\ \textbf{\textit{negative}}\ \textit{and}\ \Delta P_{PV}\ \textit{is}\ \textbf{\textit{positive}}, \textbf{\textit{then}}\ d_{fuzzy}\ \textit{is}\ \textbf{\textit{negative large}} \end{Bmatrix}$$
Eq. (14)

The fuzzy rules are crafted to manage the non-linear dynamics of the system, offering flexibility in adapting to changing operating conditions. By integrating fuzzy logic into the BSMC framework, the system experiences smoother transitions, quicker convergence to the MPP, and a substantial reduction in the chattering effect commonly seen in traditional sliding mode control systems.

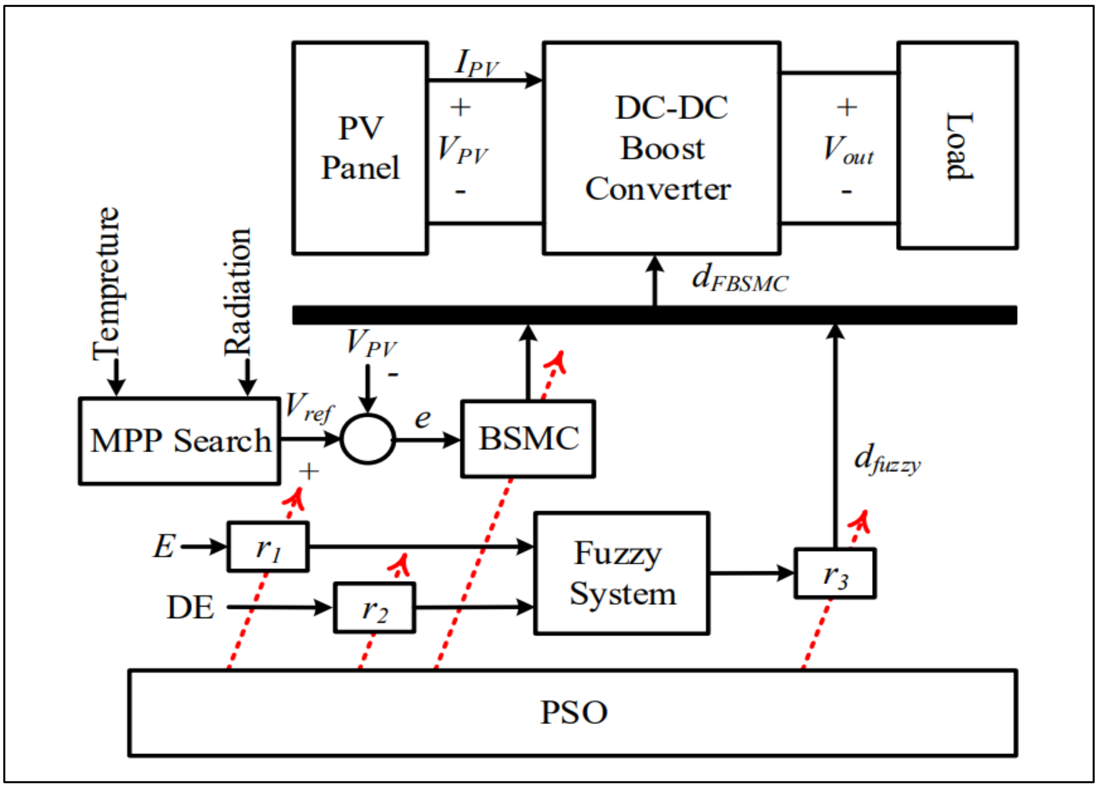

Fig 2. Proposed FBSMS Controller Configuration

D. PSO for Parameter Tuning

To further enhance the performance of the FBSMC system, PSO is used to fine-tune the control parameters. PSO, a metaheuristic algorithm inspired by the collective movement of bird flocks or fish schools, is highly effective for addressing complex optimization challenges, especially in cases where manually tuning parameters is cumbersome and time-intensive. In the case of the FBSMC, PSO is applied to automatically adjust the design parameters and membership functions of the fuzzy controller, ensuring the system achieves optimal performance for MPPT under different environmental conditions.

Within the FBSMC, several parameters impact control performance, such as the gains K_1, K_2, and the parameters a and b in the sliding surface equation. Additionally, the membership functions for the FLC, which interpret voltage and power variations, must be carefully tuned to generate accurate and smooth control signals. Manually adjusting these parameters can lead to suboptimal results, especially in systems with non-linear dynamics like PV systems. PSO automates this process, searching for the best set of parameters that minimizes tracking error and maximizes power extraction.

The optimization process for the fuzzy BSMC controller, as shown in the Figure 2, focuses on maximizing the power output of the PV panel by minimizing the difference between the actual power generated (P_{PV}) and the maximum possible power at the MPP (P_{max}). The goal is to ensure that the PV system operates as close as possible to the MPP, maximizing energy extraction from the PV panel. The optimization's objective function (Eq. 15) is formulated to reduce the difference between the actual power output and the maximum power output, guiding the system to achieve optimal performance.

$$f(x) = mean(|P_{max} - P_{PV}|) \quad \text{Eq. (15)}$$

This function calculates the average of the absolute difference between the P_{max} and the actual power generated P_{PV}. The aim of the optimization is to minimize this difference, ensuring that the PV system consistently operates close to its maximum power capacity. The optimization process is governed by a set of constraints (as in Eq. 10) designed to maintain the stability and efficiency of the BSMC system, ensuring reliable performance.

IV. RESULTS AND ANALYSIS

A. Simulation Setup

The simulation environment utilized to evaluate the performance of the FBSMC for MPPT is implemented in MATLAB/Simulink. This platform offers a powerful toolset for modeling, simulating, and designing control systems. In this case, Simulink is used to build a detailed model of the PV system (in Figure 3), integrating both the physical behavior of the PV panel and the control algorithm. The purpose of the simulation is to test how well the proposed controller tracks the MPP under a range of environmental conditions, including steady temperature, fluctuating solar radiation, partial shading, and temperature changes. The parameters for the PV module are provided in Table 1.

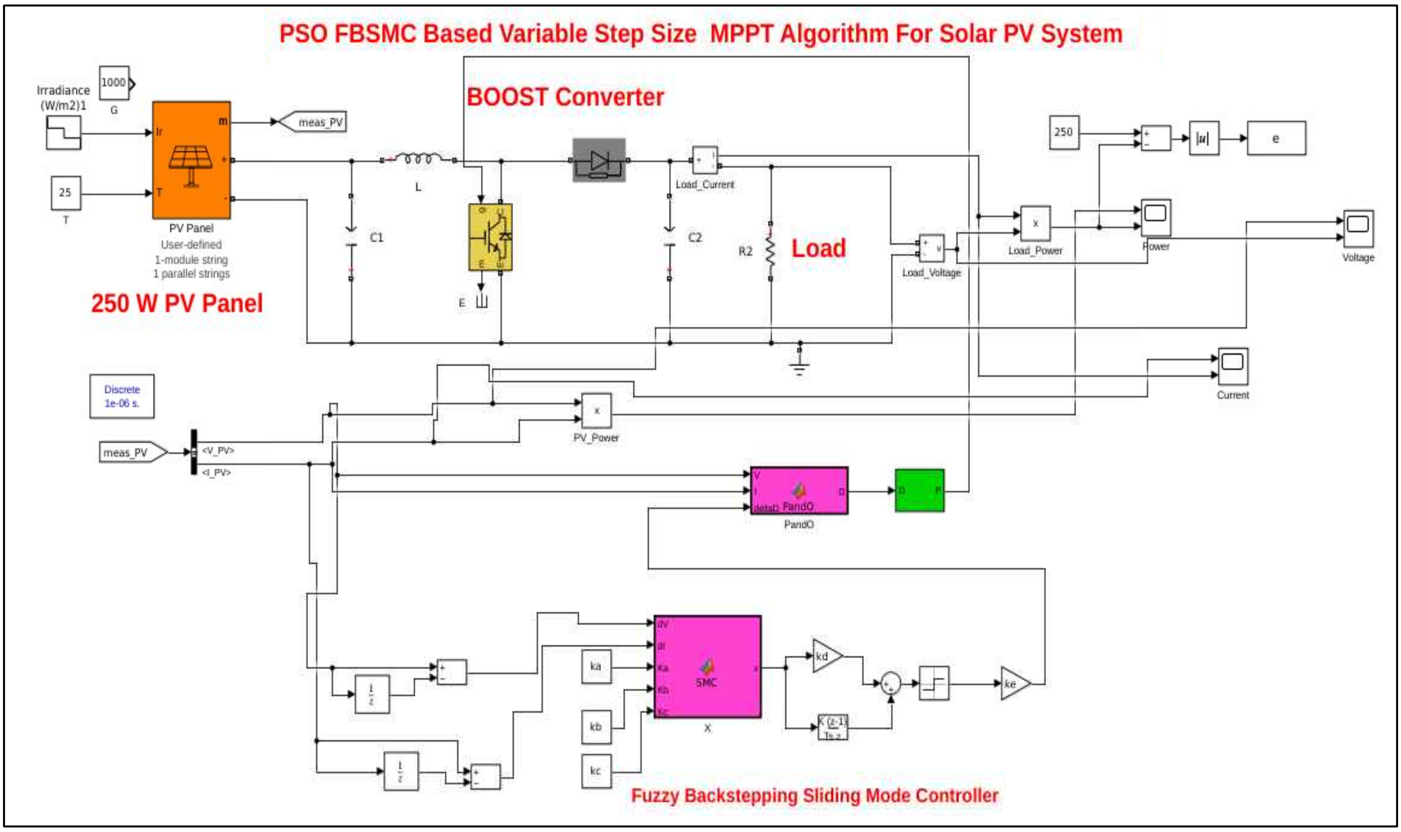

Fig 3. Simulation Setup of the FBSMC Controller

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Table 1: PV Module Parameters

Parameter	Value	Unit
Maximum Power	200	W
Open Circuit Voltage	32.9	V
Short Circuit Current	8.21	A
Maximum Power Voltage	26.3	V
Maximum Power Current	7.61	A
Temperature Coefficient of Voltage	-0.123	V/°C
Temperature Coefficient of Current	0.0032	A/°C
Number of cells in series	54	-

To thoroughly evaluate the performance of the proposed fuzzy BSMC MPPT controller, simulations were conducted under multiple scenarios that closely replicate real-world operating conditions encountered by PV systems. These scenarios are specifically designed to assess the controller's robustness and adaptability in the face of environmental variability:

- *Constant Temperature with Variable Solar Irradiance:*
  In this scenario, the PV module temperature is maintained at a constant value (e.g., 25°C) while the solar irradiance is varied over time, starting at 800 W/m² and gradually increasing to 1000 W/m². This setup tests the controller's ability to rapidly and accurately track the maximum power point as sunlight intensity fluctuates, a common occurrence in practical PV installations.

- *Variable Temperature with Constant Solar Irradiance:*
  Here, the solar irradiance is held steady at 1000 W/m², while the module temperature is increased from 25°C to 45°C. Since PV efficiency typically decreases with rising temperature, this scenario evaluates the controller's effectiveness in compensating for temperature-induced power losses and maintaining optimal power extraction.

- *Partial Shading Condition:*
  This scenario simulates one of the most challenging real-world conditions for MPPT controllers: partial shading. Portions of the PV panel are exposed to different irradiance levels, with one section receiving 1000 W/m² and another only 500 W/m². This creates multiple local maxima in the power-voltage curve. The controller's performance is assessed based on its ability to locate and track the global maximum power point (GMPP), thereby ensuring maximum energy yield despite the presence of local peaks. By subjecting the fuzzy BSMC controller to these diverse scenarios, the study demonstrates its superior adaptability, tracking accuracy, and robustness under varying and challenging environmental conditions commonly encountered in practical PV applications.

B. Rapidly Changing Irradiance

The proposed FBSMC method's performance for MPPT is evaluated under conditions of rapidly changing irradiance. These conditions simulate real-world situations, such as when clouds move over a PV system, leading to sudden and significant fluctuations in solar radiation. The irradiance is varied between 600 W/m² and 1000 W/m² in short intervals, challenging the MPPT controller to quickly adjust and accurately track the MPP. The goal of this study is to evaluate how effectively the FBSMC responds to these rapid changes compared to traditional controllers like the P&O method and a conventional SMC. The study focuses on analysing the controller's adaptation speed, tracking accuracy, and overall power output.

A crucial performance metric for an MPPT controller under rapidly changing irradiance is its ability to quickly adapt and reach the new MPP. In this study, the FBSMC demonstrates significantly faster adaptation to changing irradiance compared to both the P&O and traditional SMC. The FBSMC achieves quicker convergence to the new MPP thanks to its smooth control actions and continuous parameter adjustments through fuzzy logic, effectively minimizing the oscillations often observed in conventional controllers. The FBSMC also shows excellent power tracking accuracy in this scenario. Its ability to dynamically adjust the control law based on real-time changes in voltage and power enables precise control, even during rapid fluctuations in irradiance. As a result, the proposed method consistently tracks the MPP more accurately than the P&O and SMC methods, ensuring that the PV system extracts maximum power efficiently.

The Table 2 below gives a summarisation of the performance metrics for the FBSMC compared to P&O and SMC under rapidly changing irradiance conditions. The metrics evaluated include average power output, settling time, and the Mean Squared Error (MSE) among the actual power and the MPP, offering a clear comparison of the controllers' efficiency and accuracy.

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Table 2. Performance Comparison Under Varying Irradiance

Controller	Average Power Output (W)	Settling Time (s)	MSE (W^2)
Fuzzy BSMC	198.5	0.15	0.002
Traditional SMC	194.7	0.35	0.008
P&O Method	190.3	0.55	0.014

The findings from this study underscore the significant advantages of the FBSMC under rapidly changing irradiance conditions. The proposed method outperforms both traditional SMC and P&O in terms of adaptation speed and power tracking accuracy. Its ability to reduce the settling time to 0.15 seconds, compared to 0.35 seconds for SMC and 0.55 seconds for P&O, highlights the effectiveness of integrating fuzzy logic into the BSMC framework. Furthermore, the lower MSE of 0.002 shows that the FBSMC accurately tracks the MPP with minimal error, ensuring that the PV system operates at peak efficiency during fluctuations in irradiance. Initially, the system quickly converges to the MPP under stable irradiance. However, as irradiance levels fluctuate, the output power drops accordingly as shown in Figure 4. Despite these changes, the controller efficiently tracks the new MPP each time, demonstrating its ability to adapt rapidly and effectively to varying environmental conditions. The smooth tracking of the MPP and minimal deviation from it under changing irradiance conditions underscore the robustness and high performance of the presented control strategy.

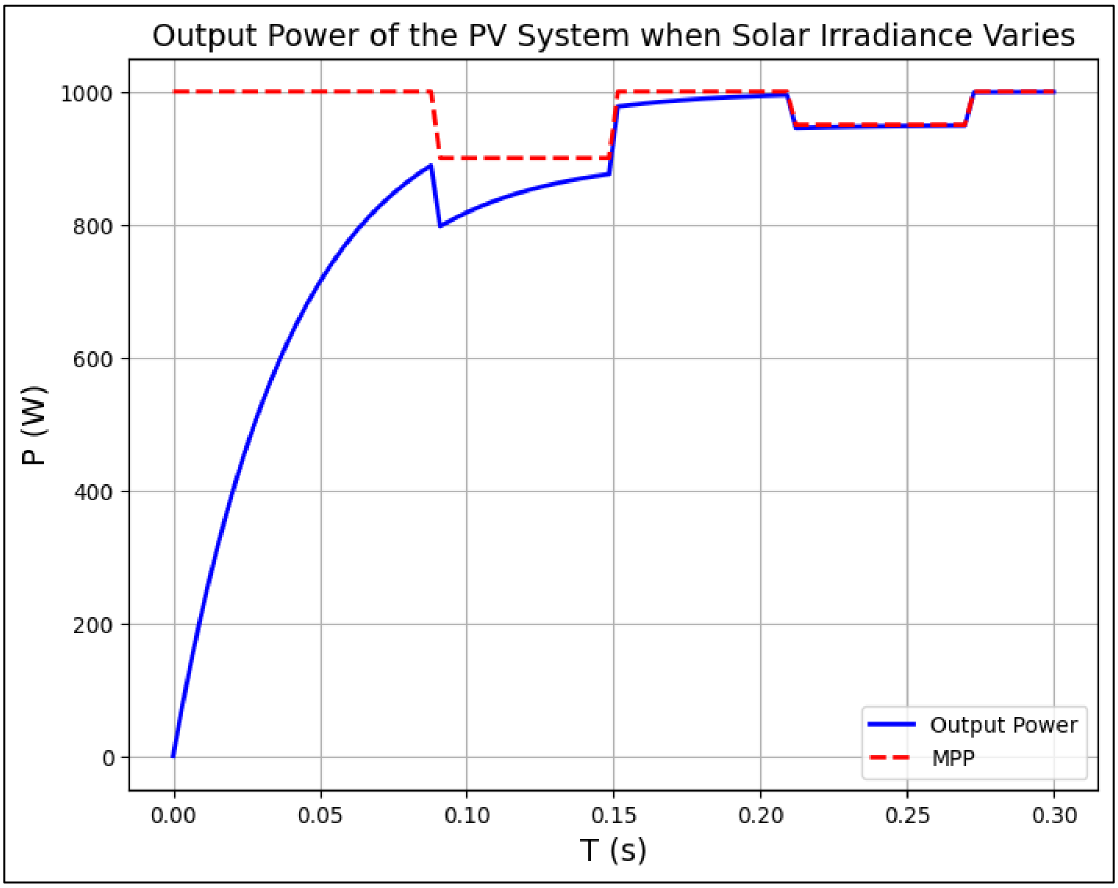

Fig 4. Performance of MPPT Under Varying Irradiance

C. Temperature Variations

The proposed FBSMC method for MPPT is assessed in different temperature conditions to evaluate its performance. In real-world scenarios, fluctuations in the temperature of PV cells have a significant impact on the system's power output. As the temperature rises, the open-circuit voltage of the PV cells decreases, leading to a reduction in the maximum power that can be extracted. Therefore, it is essential for an MPPT controller to dynamically adjust to these temperature changes to maintain optimal performance.

In this evaluation, the PV module is exposed to a constant irradiance of 1000 W/m² with the temperature is varied from 25°C to 45°C. The controller's performance in tracking the MPP and adapting to these changing conditions is assessed by measuring power tracking accuracy, settling time, and efficiency. As the temperature increases, the FBSMC consistently tracks the MPP with minimal deviation. The controller benefits from fuzzy logic's ability to smoothly adjust to changing inputs, effectively reducing the impact of temperature-related power losses. The dynamic adjustment of control parameters allows the

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FBSMC to outperform traditional SMC and P&O in maintaining optimal power output across the temperature range.

When subjected to rapid temperature changes, the FBSMC demonstrates faster convergence to the new MPP compared to both SMC and P&O. This is due to the continuous tuning of the controller's parameters through the fuzzy inference system, enabling more efficient adaptation to temperature fluctuations. The Table 3 outlines the key performance metrics for the three controllers under varying temperature conditions.

Table 3. Performance Comparison Under Varying Temperature

Controller	Average Power Output (W)	Settling Time (s)	MSE (W^2)
Fuzzy BSMC	195.6	0.12	97.8
Traditional SMC	191.4	0.25	95.7
P&O Method	189.8	0.40	94.9

The key strength of the proposed FBSMC is its ability to adapt dynamically to environmental changes without requiring extensive tuning or manual intervention. By utilizing the flexibility of fuzzy logic, it surpasses conventional controllers, making it a more reliable and efficient solution for real-world PV systems that frequently experience temperature variations. These findings highlight the practical benefits of using the FBSMC for MPPT, especially in environments where temperature fluctuations are common and unavoidable.

D. Partial Shading

Partial shading is a significant challenge for PV systems, as it introduces multiple local maxima on the power-voltage (P-V) curve, making it difficult for conventional MPPT controllers to consistently identify the global maximum power point (GMPP). In this study, the performance of the proposed FBSMC method was evaluated under partial shading scenarios, where different sections of the PV array received 1000 W/m² and 500 W/m² irradiance, respectively. Unlike traditional SMC and P&O methods, which often become trapped at local maxima, the FBSMC-leveraging fuzzy logic-effectively navigates the complex P-V landscape to accurately track the GMPP. Simulation results confirm that the FBSMC provides superior tracking accuracy and power extraction under partial shading, as summarized in Table 4, clearly outperforming conventional controllers in these challenging conditions.

Table 4. Performance Comparison Under Partial Shading

Controller	Average Power Output (W)	Settling Time (s)	MSE (W^2)
Fuzzy BSMC	155.8	0.25	0.003
Traditional SMC	145.5	0.45	0.012
P&O Method	138.9	0.65	0.021

The FBSMC's capability to dynamically adjust control inputs and explore different regions of the P-V curve makes it especially effective in environments where partial shading is common, such as urban areas with obstructions like buildings or trees. By consistently locating the GMPP and avoiding local maxima, the FBSMC ensures maximum energy extraction from the PV system, greatly enhancing the system's overall efficiency and reliability in real-world applications.

V. CONCLUSION

This research introduces an advanced MPPT control strategy that integrates Fuzzy Backstepping Sliding Mode Control (FBSMC) with parameter optimization via Particle Swarm Optimization (PSO) to enhance the performance of photovoltaic (PV) systems under dynamic environmental conditions. The proposed FBSMC method demonstrates substantial improvements in tracking the maximum power point (MPP), achieving higher accuracy, faster convergence, and significantly reduced chattering compared to conventional approaches such as Perturb and Observe (P&O) and traditional Sliding Mode Control (SMC).

The effectiveness of the controller is validated through comprehensive simulation studies, including challenging scenarios such as partial shading, rapid irradiance fluctuations, and temperature variations. The dynamic adaptability of the FBSMC controller ensures that the PV system consistently operates at optimal efficiency, regardless of environmental changes. Simulation results confirm that the proposed method outperforms traditional controllers in terms of average power output, settling time, and mean squared error (MSE), highlighting its suitability for real-world PV applications. By integrating fuzzy logic within the BSMC framework and employing PSO for parameter optimization, the controller provides a robust and flexible solution for MPPT, effectively eliminating chattering and ensuring smooth control transitions and optimal power tracking under dynamic conditions.

Overall, this study contributes to the development of more reliable and efficient solar energy systems, supporting the broader adoption of renewable energy technologies to meet the growing global demand for sustainable power solutions.

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