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Comparative Assessment of P&O, PSO Sliding Mode, and PSO-ANFIS Controller MPPT for Microgrid Dynamics

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Abstract—**This paper compares different maximum power point tracking (MPPT) control strategies in microgrid dynamics, focussing on perturb and observe (P&O), adaptive neuro-fuzzy inference system (ANFIS), particle swarm optimisation (PSO), and PSO sliding mode controller techniques. The study investigates their performance under varying microgrid conditions, considering factors like weather and load variations. The simulation results provide a detailed comparative analysis of the power at the point of common coupling (PCC) for MPPT techniques at different time intervals. Both the P&O and PSO sliding mode recorded a power output of 287 kW, while PSO-ANFIS achieved a slightly higher power output of 294 kW. At 2.5 seconds, the P&O method recorded a power output of 712 kW, while the PSO sliding mode and the PSO-ANFIS techniques achieved 717 kW and 738 kW, respectively. Overall, the PSO-ANFIS technique consistently outperformed the other methods in terms of power output, demonstrating its effectiveness in maximising energy extraction and adaptability to dynamic conditions. These findings provide valuable insights for designing and implementing MPPT controllers in microgrid systems, emphasising the efficiency of the hybrid PSO-ANFIS technique in enhancing the overall performance and stability of renewable energy systems.**

Index Terms—**Energy storage; Maximum power point trackers; Microgrids; Solar energy.**

I. INTRODUCTION

In the pursuit of optimising the performance and efficiency of microgrid systems, the application of advanced control strategies for maximum power point tracking (MPPT) has become a focal point of research. This paper presents a comprehensive investigation into the comparative assessment of three distinct MPPT methodologies: perturb and observe (P&O), adaptive neuro-fuzzy inference system (ANFIS), and particle swarm optimisation (PSO) along with the innovative PSO sliding mode controller. Microgrid dynamics inherently pose challenges with varying environmental conditions and load fluctuations, necessitating an in-depth exploration of controller effectiveness. The primary objective of this investigation is to scrutinise the performance of these controllers in dynamic microgrid scenarios, with the aim of discerning their strengths, weaknesses, and relative efficacy in optimising energy extraction. By leveraging simulation-based analyses, this research contributes insights into the nuanced dynamics of microgrid operation and assists in delineating the most suitable MPPT control strategy. Inclusion of the PSO sliding mode controller, a novel approach in this context, further enriches the comparative analysis. The findings presented herein promise to inform the design and implementation of robust MPPT controllers, thereby advancing recent research in microgrid regulation policies and fostering the efficient incorporation of nonconventional energy into contemporary power systems.

Within the realm of microgrid energy management systems, numerous methodologies have been devised to enhance the operational efficiency of microgrids relying on photovoltaic sources. One such technique is the adaptive P&O MPPT system, which has been proven to be effective in achieving high performance in microgrid systems [1]. This technique utilises a control algorithm that continuously perturbs the operational point of the photovoltaic (PV) scheme and observes the resulting power output to determine the extreme power point. By dynamically adjusting the perturbation step size based on the system's operating conditions, the adaptive P&O MPPT technique can successfully trace the extreme power point and optimise the energy harvesting efficiency of the microgrid. Another approach to improving the performance of microgrid energy management systems is the use of interleaved boost converters in conjunction with the P&O MPPT technique. The authors in [2] propose the integration of an interleaved boost converter into the microgrid system to enhance power conversion efficiency and reduce voltage ripple. This configuration allows for the distribution of power across multiple converter stages, thereby lowering the current stress on every converter and improving the overall scheme efficiency. The P&O MPPT method is then used to trail the extreme power point of the photovoltaic system, ensuring optimal energy harvesting in the microgrid. The authors in [3] propose a neural network estimator-based MPPT system for photovoltaic panels, demonstrating improved accuracy and performance, achieving nearly 99 % of the maximum power. In [4], an adaptive calculation block and fuzzy logic controller MPPT approach are introduced for photovoltaic

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panels that outperform previous accuracy, speed, and efficiency methods.

In recent years, researchers have also explored the attention of PSO algorithms in combination with the P&O MPPT performance for microgrid systems. The authors in [5]–[7] propose a high performance adaptive PSO MPPT method specifically designed for photovoltaic-based microgrids in rural areas. The PSO procedure is utilised to dynamically modify the perturbation step size of the P&O MPPT method based on the system's operating conditions, allowing efficient trailing of the extreme power point even in challenging environmental circumstances.

The integration of ANFIS and PSO to achieve MPPT in PV grid integration represents one specific approach. An experimental estimate of an MPPT procedure based on the hybrid ANFIS-PSO was conducted by the authors in [8]. The study aimed to expand the proficiency of PV systems by accurately trailing the maximum power point under varying sun irradiance conditions. The efficiency of the suggested approach in enlightening the performance of PV grid integration systems was demonstrated by the results. Similarly, a PSO-based adaptive neuro-fuzzy inference scheme for controlling extreme power point trailing in a three-phase grid-integrated photovoltaic scheme was proposed by the authors in [9]. The focus of the study was on optimising the output power of the PV scheme through dynamic adjustment of the working point to reach the extreme power point. The performance of the planned method was observed to exceed that of traditional MPPT techniques, as indicated by the results. In the realm of AC microgrids, a power management strategy founded on ANFIS was formulated by the authors in [10]. The objective of the strategy was to optimise power flow and confirm steady operation of the microgrid. The results illustrated the effectiveness of the approach in enhancing the overall performance and stability of the AC microgrid. Additionally, the authors in [11] suggested a novel cooperative regulator method for converters in hybrid AC/DC smart microgrids. The aim of the technique was to improve power quality and microgrid stability by coordinating the operation of multiple converters. The results of the proposed technique evidenced superior performance in power sharing and voltage regulation, compared to conventional control methods. The enhancement of the dynamic response of a robust sliding mode MPPT controller, utilising the PSO procedure for PV schemes under fast-varying environmental circumstances, was the focus of a work in [12]. The objective of the learning was to expand the trailing accuracy and response speed of the MPPT controller. The results indicated that the proposed approach outperformed traditional methods in terms of tracking proficiency and stability.

Within the realm of power generation systems designed for microgrid applications, the emergence of sliding mode control stands out as a promising approach. As a robust control technique, sliding mode control proves adept at efficiently governing the operation of microgrid-based photovoltaic power generation systems. The utilisation of this control strategy guarantees system stability and optimal performance, even in the face of uncertainties and disturbances. Researchers have conducted widespread lessons regarding the application of sliding mode regulators within microgrid systems. For example, the sliding mode regulator of power generation systems based on photovoltaics for microgrid applications was explored by the authors in [13]. They proposed a sliding mode control strategy to effectively manage the power flow and preserve the stability of the microgrid system. The effectiveness of sliding mode control in enhancing the performance of power generation systems based on photovoltaics in microgrids was demonstrated by the study. Similarly, the dynamic process and regulation of hybrid power schemes in microgrids were investigated by the authors in [14]–[17]. They explored the incorporation of nonconventional sources and storage energy schemes in microgrids and proposed a control plan based on sliding mode control. The study emphasised the advantages of sliding mode control in optimising the operation of hybrid power systems in microgrids. These investigations contribute to the progression of sliding mode regulator techniques within the domain of power generation systems in microgrids. Through the application of the sliding mode regulator, microgrids can achieve improved strength, reliability, and efficiency in utilising nonconventional energy sources. The advanced fuzzy-PSO method for optimising energy management in hybrid microgrids was suggested in [18], while the authors in [19] directed attention to the modelling of a grid-integrated microgrid scheme incorporating PV and battery components, along with an MPPT controller. The insights gained from these research endeavours hold significance for the progress of sustainable power distribution and the incorporation of nonconventional energy sources into microgrid systems. In [20], a reduced oscillation perturb and observe (ROP&O) MPPT technique was proposed for photovoltaic panels, achieving 99.06 %–99.80 % efficiency with faster convergence and improved power quality compared to conventional methods.

The primary objective of this study is to conduct a comprehensive investigation of the comparative performance of various MPPT techniques within microgrid systems. Specifically, the study seeks to evaluate the effectiveness of P&O, ANFIS, PSO, and the innovative PSO sliding mode controller. By examining these controllers in dynamic microgrid scenarios characterised by varying environmental conditions and load fluctuations, the study aims to discern their strengths, weaknesses, and relative efficacy in optimising energy extraction. This research aims to provide valuable insights into the nuanced dynamics of microgrid operation and assist in identifying the most suitable MPPT control strategy for real-world applications.

Contribution of the paper. The paper presents a detailed comparative assessment of three widely used MPPT methodologies (P&O, ANFIS, and PSO) along with the novel PSO sliding mode controller. This analysis highlights the strengths and limitations of each approach under dynamic microgrid conditions. By introducing and evaluating the PSO sliding mode controller, a novel approach in the context of MPPT for microgrids, the study assesses its potential to enhance tracking accuracy and robustness in energy extraction. Through extensive simulation-based analyses, the research provides information on the performance of different MPPT controllers in optimising energy harvesting efficiency and stability in microgrids, considering various environmental and operational conditions.

Furthermore, the study evaluates adaptive techniques like the PSO-ANFIS approach, demonstrating its superior performance in tracking the maximum power point under varying conditions. The research underscores the benefits of combining ANFIS and PSO to enhance MPPT accuracy and robustness. The findings of this study offer valuable guidance for the design and implementation of robust MPPT controllers in microgrid systems, contributing to the advancement of microgrid regulation policies and the efficient incorporation of nonconventional energy sources into contemporary power systems. Additionally, the paper synthesises recent research on various MPPT and control techniques, providing a comprehensive overview of current advances and methodologies, thus contextualising the study findings within the wider landscape of research on microgrid energy management.

II. PROPOSED SYSTEM

Figure 1 describes the block diagram of the suggested system.

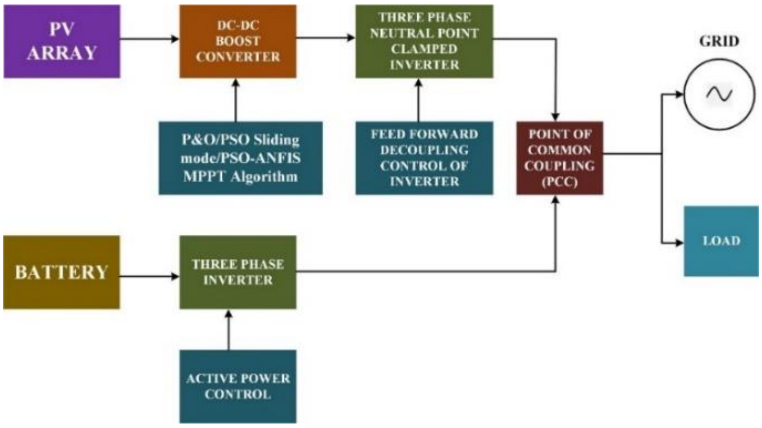

Fig. 1. Microgrid system with grid, PV, and battery scheme.

The grid-tied solar inverter system comprises several key components, as illustrated in the diagram, designed to efficiently convert solar energy into usable electricity. The PV array captures sunlight and generates DC electricity, which is then elevated to a suitable voltage by the DC-DC boost converter. The three-phase inverter transforms this DC electricity into AC electricity, and the neutral point clamped inverter ensures the prevention of unwanted DC currents in the neutral conductor of the AC system. A crucial element is the MPPT algorithm, which optimises power production by tracking the extreme power point of the PV array. The feed-forward control system regulates the output voltage of the inverter. The point of common coupling (PCC) represents the connection point to the AC grid. Additionally, the system may incorporate a battery to store excess solar energy for later use, and a secondary three-phase inverter converts the stored DC electricity from the battery into AC electricity. The active power control system manages the exported power to the grid. Information and energy flow seamlessly between these components, exemplified by signals from the MPPT algorithm that adjust the DC-DC boost converter voltage and the feed-forward control system that influences the inverter output voltage, showcasing the integrated functionality of the entire solar inverter scheme.

A. PV Modelling

Figure 2 shows the electrical circuit of the PV cell, which includes a current source (I_p) for the photocurrent and intrinsic shunt (R_{sh}) and series (R_{se}) resistances. R_{sh} is usually high and R_{se} is low, so their neglect simplifies the analysis. PV cells are connected in series or parallel to form PV arrays

$$I_p = \lfloor I_{sc} + K_i (T - 298) \rfloor \times I_r / 1000. \tag{1}$$

Cell photocurrent (I_p) is measured in amperes (A). A crucial parameter, short-circuit current (I_{sc}), is expressed in amperes. The normal cell short-circuit current at 25 °C and 1000 W/m^2 is K_i. T is the operational temperature in Kelvin (K), and I_{rs} is the reverse saturation current the solar module

$$I_{rs} = I_{sc} / \left\lfloor \exp\left(\frac{qV_{oc}}{N_s knT}\right) - 1 \right\rfloor. \tag{2}$$

A fundamental unit is the electron charge (q) of 1.6×10^{-19} C. The charge is used to calculate open-circuit voltage (V_{oc}). The number of series-connected cells (N_s) affects the system. The ideality factor of the diode, N, is a crucial parameter. The Boltzmann constant ($K = 1.3805 \times 10^{-23}$ J/K) is important for the thermal properties of the system.

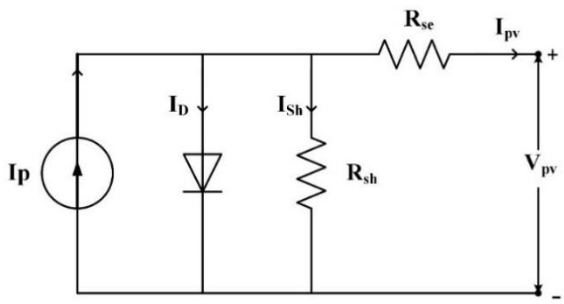

Fig. 2. Electrical circuit of the PV cell.

B. DC-DC Boost Converter

The DC-DC converter (Fig. 3) allows PV scheme extreme power trailing and load adjustment. The boost converter generates a controlled high DC output for the load by storing energy in an inductor. The voltage drop across the inductor varies with current. This setup optimises system performance by transferring and regulating energy.

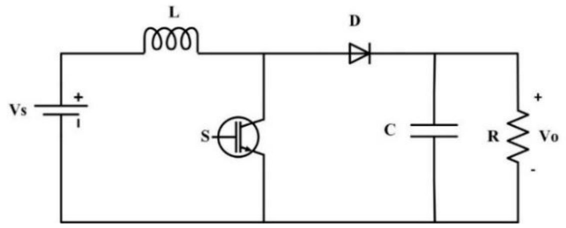

Fig. 3. A model of the boost converter.

C. Battery

Numerous research publications extensively cover various battery types, including nickel-metal-hydride, lithium-ion, lead acid, and sodium nickel chloride batteries. The focus of the modelling is on a redesigned and improved version of the lithium-ion battery, considering the impact of double-layer diffusion and Coulomb's coefficient. The equivalent circuit of the battery consists of an internal resistance that simulates the ohmic resistance, a series DC voltage source, and two parallel branches connected in series to replicate both electrochemical and electromagnetic effects. When a lithium battery is discussed, the three crucial factors to consider are the state of charge (SOC %), the remaining usable life, and the degradation. Additionally, other factors such as battery parameter detection, charge management, and monitoring and alert systems for battery security should be considered.

D. Three-Phase Inverter and Control

Figure 4 depicts a three-phase neutral point clamped inverter (NPC), which is a multilevel inverter designed for high-power and efficient applications. This inverter is known for its ability to generate a stepped voltage waveform at the output by connecting each phase to a neutral point through clamping diodes. The NPC inverter uses multiple voltage levels achieved through different switching states to approximate a sinusoidal waveform. Compared to traditional two-level inverters, the neutral point clamped configuration reduces the voltage stress on the switching components, improving overall efficiency and reliability. In the NPC inverter, each phase is divided into two voltage levels using the neutral point. When a set of switches in a phase leg is activated, the voltage across the load is determined by the clamped neutral point, allowing for the generation of multiple output voltage levels and a more refined synthesised waveform. The NPC inverter is well suited for applications requiring low harmonic distortion, such as renewable energy systems and motor drives, due to its capability to produce high-quality output voltage. Additionally, the balanced neutral point voltage in the NPC configuration contributes to enhanced system stability and performance.

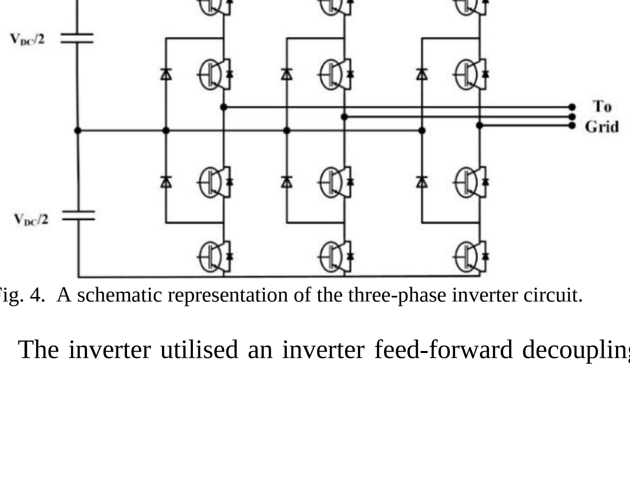

Fig. 4. A schematic representation of the three-phase inverter circuit.

The inverter utilised an inverter feed-forward decoupling control and an active power control method to deliver switching pulses to the inverter switches.

III. MPPT IN MICROGRID DYNAMICS

The extreme power point trailing is pivotal for the success of microgrid structures, particularly those that incorporate renewable energy sources. Maximum power point tracking (MPPT) optimises energy harvesting by extracting the maximum power from sources like solar panels and wind turbines, ensuring peak efficiency and reducing reliance on nonrenewable energy. It plays a vital role in mitigating variability in renewable sources, adapting to changing conditions, and contributing to grid stability when microgrids are interconnected with larger utility grids. The economic viability of microgrids is enhanced because MPPT allows cost-effective use of renewable energy, leading to long-term operational savings.

A. P&O MPPT Control

The perturb and observe (P&O) algorithm is a widely used method to maximise the power output of a PV system. The algorithm works by periodically perturbing (i.e., slightly increasing or decreasing) the voltage of the PV system and observing the effect on the power output. If the perturbation results in an increase in power, the change is kept; if not, the direction of the perturbation is reversed in the next iteration. The process can be summarised by the following steps:

1. Perturb the PV system voltage V slightly;
2. Measure the change in the power output Delta P;
3. If Delta P > 0, continue perturbing in the same direction;
4. If Delta P < 0, reverse the direction of perturbation;
5. Repeat the process to keep the PV system operating at its maximum power point (MPP).

B. PSO Sliding Mode Control

The procedure of particle swarm optimisation (PSO) sliding mode control MPPT involves several steps that integrate PSO with sliding mode control (SMC) to optimise the power generation of photovoltaic (PV) systems in a microgrid context:

1. Initialisation: Start by setting up PSO with parameters like population size and maximum iterations;
2. Particle setup: Randomly initialise particles within the feasible range of SMC control parameters;
3. Evaluate fitness: Calculate each particle's fitness using a function that maximises PV system power;
4. Update bests: Keep track of the best global and personal solutions for each particle;
5. Optimise movement: Adjust particle positions and velocities based on global and personal bests;
6. Adjust control parameters: Use the optimised particle positions to adjust SMC control parameters;
7. Implement SMC: Apply the updated SMC settings to guide the PV system to its maximum power point;
8. Iterate and Converge: Repeat the process until satisfactory MPPT performance is achieved, maximising power output and system stability.

C. PSO-ANFIS MPPT Control

ANFIS MPPT: Widely employed in photovoltaic systems, the adaptive neuro-fuzzy inference system (ANFIS) for MPPT represents an intelligent control approach. Complex relationships are adaptively modelled using a combination of fuzzy logic and neural networks within the ANFIS framework, rendering it well suited for optimising the operational point of solar panels. The ANFIS architecture, as depicted in Fig. 5, typically comprises five layers.

The input variables, denoted as $I_{ij}^{(1)}$, are fuzzified using membership functions μ_j. Each node in this layer computes the membership value $o_{ij}^{(1)}$ using the equation

$$o_{ij}^{(1)} = \mu_j\left(I_{ij}^{(1)}\right). \quad (3)$$

The second layer, often called the fuzzy and operation layer, calculates the firing strength $o_k^{(2)}$ for each rule by taking the product of the fuzzy membership values

$$o_k^{(2)} = \omega_k = \Pi_{i=1}^{q} o_{ij}^{(1)}. \quad (4)$$

The third layer normalises the firing strengths to ensure a fair contribution to the output. The normalised firing strength $o_k^{(3)}$ is given by

$$o_k^{(3)} = \overline{\omega_k} = \frac{o_k^{(2)}}{\sum_{m=1}^{y^2} o_m^{(2)}}. \quad (5)$$

The fourth layer comprises nodes with linear parameters. Each node k applies a linear function to the normalised firing strength to obtain the output $o_k^{(4)}$

$$o_k^{(4)} = \overline{\omega_k} f_k = \overline{\omega_k}\left(d_{1k} I_1^{(1)} + d_{2k} I_2^{(1)} + \ldots + d_{yk} I_y^{(1)} + d_0\right). \quad (6)$$

The fifth layer has a single node that sums up the outputs from Layer 4 to generate the overall network output U_a

$$U_a = o^5 = \sum_{k=1}^{y^2} o_k^{(4)} = \sum_{k=1}^{y^2} \overline{\omega_k} f_k = \frac{\sum_{k=1}^{y^2} \omega_k f_k}{\sum_{k=1}^{y_2} \omega_k}. \quad (7)$$

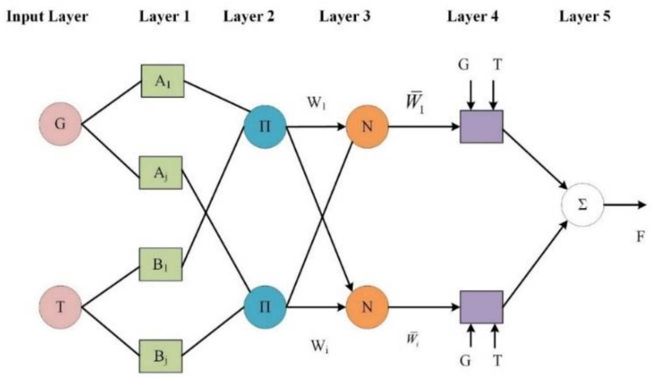

Fig. 5. Layers of the ANFIS technique.

PSO-tuned ANFIS MPPT: An advanced method to exploit the productivity of solar systems is PSO-tuned ANFIS for MPPT.

As a hybrid intelligent scheme, ANFIS combines the interpretability of fuzzy logic systems with the learning power of neural networks. The PSO procedure is used to fine-tune the parameters of the ANFIS model, enhancing its ability to accurately predict the optimal working point of the photovoltaic system. The MPPT process can be mathematically expressed as follows.

Let V_{mpp} be the voltage at the extreme power point, I_{mpp} be the corresponding current, and P_{mpp} be the extreme power.

The ANFIS model takes the form

$$P_{mpp} = f\left(V_{mpp}, I_{mpp}\right). \quad (8)$$

The factors of the ANFIS model, denoted as θ, are tuned by the PSO algorithm. The PSO update equations are given by

$$\theta_{new} = \theta_{old} + PSO\_coeff \times \left(global_{best} - \theta_{old}\right), \quad (9)$$

where PSO_coeff is a coefficient that controls the update step size, and $global_{best}$ represents the best solution found by the PSO algorithm. The PSO-tuned ANFIS MPPT system leverages the global search capability of PSO to optimise the ANFIS parameters, providing an adaptive and intelligent MPPT strategy that accurately tracks the varying operating conditions of the photovoltaic system. This integration enhances the efficiency of energy harvesting by ensuring that the PV structure operates at its extreme power point under changing environmental circumstances. The parameter details used in PSO are maximum number if iteration is 100, number of swarm particles is 50, C1 and C2 are 2, and inertia is 0.2. The grid partition ANFIS model is used with five input membership functions. The flow chart of the tuned ANFIS model is depicted in Fig. 6.

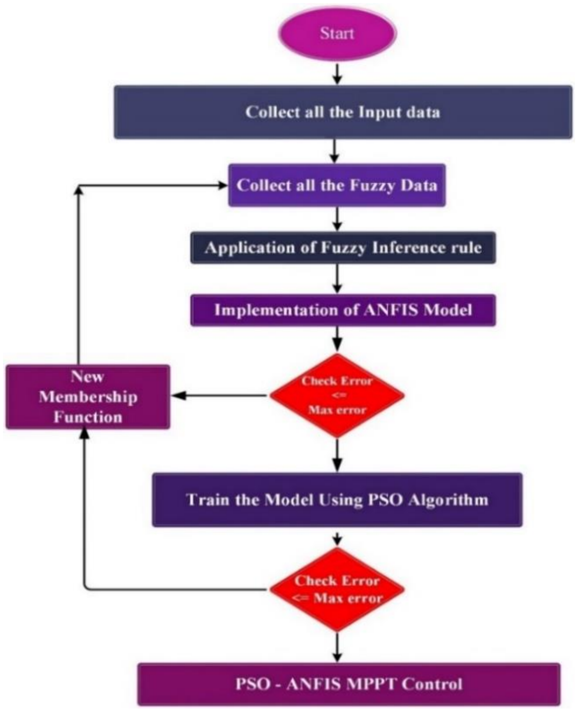

Fig. 6. Flow chart of the PSO-tuned ANFIS model.

IV. RESULTS AND DISCUSSION

Simulation of this microgrid dynamics is performed in MATLAB/Simulink. Table I provides the specifications used in the simulation. It includes details about the photovoltaic (PV) system, such as the voltage at maximum power point

(Vmp), current at maximum power point (Imp), and maximum power output, along with the configuration of PV modules in terms of series-connected modules per string and parallel strings. Additionally, it lists parameters for the PV boost converter, including inductance, capacitance, and switching frequency. The table also presents information about the battery, including its nominal voltage, rated capacity, initial state of charge, and response time. Furthermore, it mentions details about the inverter type, specifically a three-level neutral point clamped inverter (NPC), and provides specifications for the grid, such as transformer rating, grid rating, and grid frequency.

The simulation results for three different MPPT procedures, namely perturb and observe (P&O), PSO sliding mode control, and PSO-ANFIS control, are presented in the figures. In Case 1 (Fig. 7), the P&O MPPT algorithm demonstrates its performance. Case 2 in Fig. 8 showcases the MPPT with PSO sliding mode controller. Finally, Case 3 in Fig. 9 displays the results of the PSO-ANFIS MPPT procedure. These figures provide visual insight into the efficacy of each MPPT technique, allowing for a comparative analysis of its performance.

– *Case 1: With P&O MPPT algorithm*

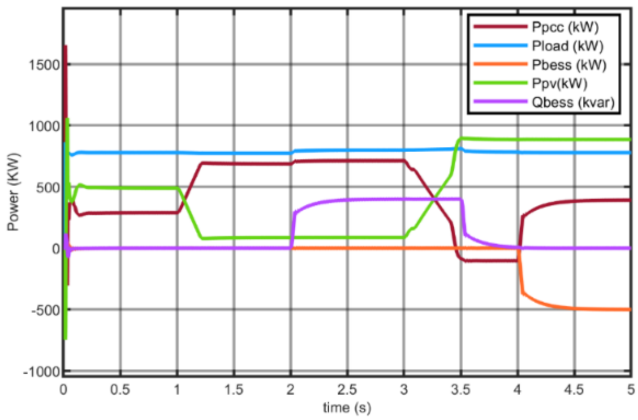

Fig. 7. Simulation results power at PCC, load power, battery power, PV power, and reactive power with P&O MPPT.

– *Case 2: With PSO sliding mode control*

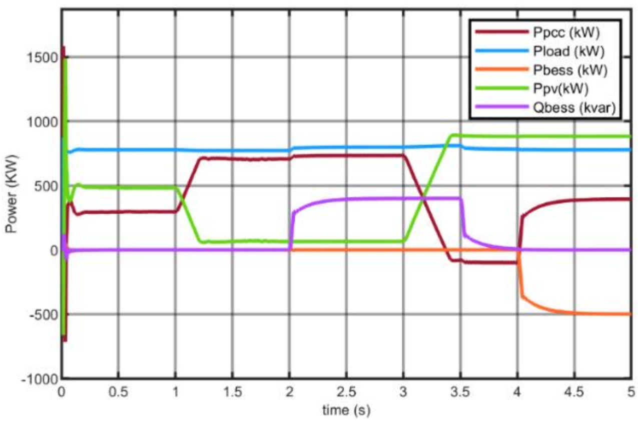

Fig. 8. Simulation results power at PCC, load power, battery power, PV power, and reactive power with PSO sliding mode controller MPPT.

In all cases, the power at the point of common coupling (P_{pcc}), the load power (P_L), the battery energy storage power (P_{bess}), the solar PV power (P_{pv}), and the reactive power (Q_{bess}) are presented.

– *Case 3. With PSO-ANFIS MPPT*

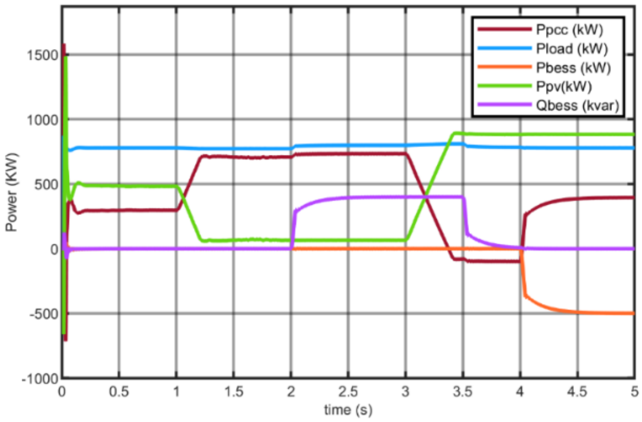

Fig. 9. Simulation results power at PCC, load power, battery power, PV power, and reactive power with PSO-ANFIS MPPT.

TABLE I. PARAMETERS OF SIMULATION.

Sl. No.	Specifications	Value
	PV Details	
1	Voltage at maximum power point Vmp (V)	43.4
2	Current at the maximum power point Imp (A)	8.18
3	Maximum power (W)	355.012
4	No. of series-connected modules per string	15
5	No. of parallel strings	190
	PV Boost Converter Details	
6	Inductance (mH)	1
7	Capacitance (mF)	0.2
8	Switching frequency (KHz)	10
	Battery Details	
9	Nominal voltage (V)	922
10	Rated capacity (Ah)	1120
11	Initial state of charge (%)	50
12	Battery response time (s)	30
	Inverter Details	
13	Type	three-level NPC
	Grid Details	
14	Transformer rating	120/27 KV, 47 MVA
15	Grid rating	120,2500 MVA
16	Grid frequency (HZ)	50

Table II provides a comparative analysis of the power at PCC for three different MPPT techniques: P&O, PSO sliding mode, and PSO-ANFIS, as derived from Fig. 10.

TABLE II. COMPARISON OF POWER AT PCC FOR DIFFERENT TIME INTERVALS.

MPPT TECHNIQUES	**Power at PCC in (kW) for different time intervals**				
	0.5 s	**1.5 s**	**2.5 s**	**3.8 s**	**4.5 s**
P&O	287	688	712	-102	383
PSO sliding mode	287	695	717	-101	386
PSO-ANFIS	294	706	738	-98	387

Power values at various time intervals, 0.5 seconds, 1.5 seconds, 2.5 seconds, 3.8 seconds, and 4.5 seconds, are presented in kilowatts (kW). At the 0.5-second mark, both P&O and PSO sliding mode record a power output of 287 kW, whereas PSO-ANFIS achieves a slightly higher power output of 294 kW. By the 1.5-second interval, the power output for P&O is 688 kW, while PSO sliding mode and PSO-ANFIS show higher values of 695 kW and 706 kW, respectively. This indicates the superior performance of PSO-ANFIS in capturing more power from the PV system during this period.

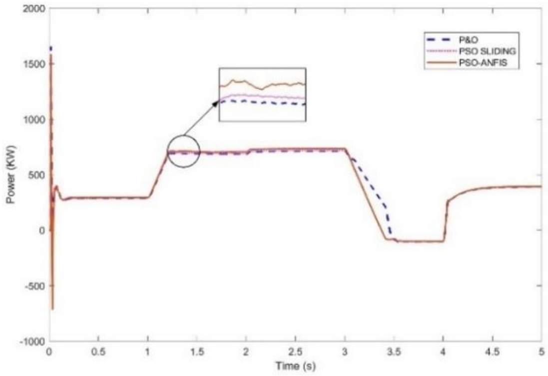

Fig. 10. Comparison of power at PCC for P&O, PSO Sliding mode, and PSO-ANFIS MPPT control.

As time progresses to 2.5 seconds, the P&O method records a power output of 712 kW, while the PSO sliding mode and the PSO-ANFIS techniques achieve 717 kW and 738 kW, respectively. However, a significant drop in power output is observed at 3.8 seconds, where P&O, PSO sliding mode, and PSO-ANFIS record -102 kW, -101 kW, and -98 kW, respectively, suggesting a transient disturbance or shading effect. Despite this dip, PSO-ANFIS shows a lesser negative impact compared to the other methods. At the final interval of 4.5 seconds, P&O records a power output of 383 kW, PSO sliding mode - 386 kW, and PSO-ANFIS - 387 kW. Overall, the PSO-ANFIS technique consistently outperforms the other methods in terms of power output, demonstrating its effectiveness in maximising energy extraction and adaptability to dynamic conditions.

V. CONCLUSIONS

The performance comparison of the maximum power point tracking (MPPT) techniques, including perturb and observe (P&O), PSO sliding mode, and PSO-ANFIS, in Table I reveals significant insights. PSO-ANFIS consistently outperforms P&O and PSO sliding mode, with power values ranging from 294 kW to 387 kW across different time intervals, showcasing its superior capabilities in maximising power output and adapting to transient conditions. Specifically, at 1.5 seconds, PSO-ANFIS achieved a power output of 706 kW compared to 688 kW and 695 kW for P&O and PSO sliding mode, respectively. This comparative study underscores the effectiveness of the PSO-ANFIS approach, which combines the strengths of PSO and ANFIS for precise MPPT with superior tracking accuracy and robustness. The competitive performance of the PSO sliding mode controller further enhances the findings. The hybrid PSO-ANFIS strategy not only optimises energy extraction in dynamic microgrid scenarios, but also showcases its potential for real-world applications. These insights contribute significantly to ongoing advancements in microgrid control strategies, offering valuable guidance for designing and implementing MPPT controllers in renewable energy systems. The hybrid PSO-ANFIS strategy stands out as a key contributor to enhancing overall performance and stability in microgrid operations, facilitating more efficient and sustainable integration of nonconventional energy resources.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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