frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 02 November 2023
DOI 10.3389/fenrg.2023.1288486

Check for updates

OPEN ACCESS

EDITED BY
Sudhakar Kumarasamy,
Universiti Malaysia Pahang, Malaysia

REVIEWED BY
Janandra Krishna Kishore Dokala,
Alliance University, India
Wang Jinming,
Zhejiang Shuren University, China

*CORRESPONDENCE
Sohrab Mirsaeidi,
msohrab@bjtu.edu.cn

RECEIVED 04 September 2023
ACCEPTED 18 October 2023
PUBLISHED 02 November 2023

CITATION
Khan M, Raza MA, Jumani TA, Mirsaeidi S, Ali A, Abbas G, Touti E and Alshahir A (2023), Modeling of intelligent controllers for solar photovoltaic system under varying irradiation conditions.
Front. Energy Res. 11:1288486.
doi: 10.3389/fenrg.2023.1288486

Modeling of intelligent controllers for solar photovoltaic system under varying irradiation conditions

Malhar Khan[1], Muhammad Amir Raza[1], Touqeer Ahmed Jumani[1], Sohrab Mirsaeidi[2]*, Aamir Ali[3], Ghulam Abbas[4], Ezzeddine Touti[5] and Ahmed Alshahir[6]

[1]Department of Electrical Engineering, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan, [2]School of Electrical Engineering, Beijing Jiaotong University, Beijing, China, [3]Department of Electrical Engineering, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Sindh, Pakistan, [4]School of Electrical Engineering, Southeast University, Nanjing, China, [5]Department of Electrical Engineering, College of Engineering, Northern Border University, Arar, Saudi Arabia, [6]Department of Electrical Engineering, College of Engineering, Jouf University, Sakakah, Saudi Arabia

The increasing demand for solar renewable energy resources, driven by the global energy crisis and the depletion of conventional energy sources, has underscored the importance of harnessing solar energy. Solar photovoltaic (PV) systems, however, exhibit nonlinear output power due to their weather-dependent nature, impacting overall system efficiency. This study focuses on the development and comparative analysis of three intelligent Maximum Power Point Tracking (MPPT) controllers using the MATLAB Simulink. The controllers employ distinct methodologies, namely, Artificial Neural Networks (ANN), Adaptive Neural and Fuzzy Inference System (ANFIS), and Fuzzy Logic Controller (FLC). The results demonstrate that ANFIS achieved the highest accuracy at 99.50%, surpassing ANN and FLC with accuracies of 97.04% and 98.50%, respectively, thus establishing ANFIS as the superior MPPT controller. Additionally, the positives and negatives of all three MPPT-based algorithms are also compared in this work.

KEYWORDS

solar power tracking, artificial neural networks, adaptive neural and fuzzy inference system, fuzzy logic controller, MATLAB

1 Introduction

The convergence of factors such as global warming, the limited availability of fossil fuels, political unrest in key fuel-producing countries, and the declining cost of generating energy through renewable technologies has led to the belief that renewable energy has the potential to effectively meet the ever-increasing global energy needs (Qazi et al., 2019; Raza et al., 2023a) The power producers have shifted their focus to Renewable Energy Technology (RET) design, application, and maximum use, because of the rapid development of RETs (Raza et al., 2022a; Raza et al., 2023b). It is strongly advised to continue investing in and studying ways that can improve the efficiency and stability of renewable energy sources (Alam et al., 2022; Raza et al., 2022b; R et al., 2022). Among all RETs the solar photovoltaic (PV) system is vastly used in the modern world because it is a clean form of energy, needs less maintenance, requires less space, and produces negligible noise (Izam et al., 2022; Raza et al., 2022c). However the main problem with solar PV panels is low energy conversion efficiency because of its weather-intermittent nature, the output is solely dependent on variable weather conditions which leads to declined efficiency (Zhou et al., 2019; Raza et al., 2022d). In order to have an improved and tracked efficiency the maximum power point tracking system is needed, and therefore several MPPT algorithms are being used (Awan, 2022). This work includes the design of three controllers that are based on ANN, ANFIS, and FLC maximum power point tracking control algorithms using MATLAB SIMULINK. The reason behind the selection of these techniques is their potential to enhance solar photovoltaic (PV) system efficiency through adaptability and AI-based optimization. The wide use of AI-based techniques necessitates the need for a comprehensive comparative study to ensure the use of optimal MPPT controllers and maintain continuous power generation from solar PV systems. Therefore, our study aimed to conduct a comprehensive comparative analysis of these intelligent controllers by applying real environment and varying weather scenarios and aligning with current research trends in renewable energy. Our unique contribution lies in rigorously assessing their performance under varying irradiance conditions and providing quantitative results, shedding light on the suitability of these controllers for practical applications in standalone PV systems. This research aims to offer decision-makers and solar energy consumers a comprehensive understanding of the principles behind MPPT, the various factors that impact it. With this being said, the following were said to be the fundamental goals of this work: to evaluate the capability of several intelligent controllers to track their maximum power under varying irradiance conditions and under both stable and unstable weather situations such as varying irradiance and constant temperature values. To investigate how a PV solar array's power output is affected by temperature and irradiance. The analysis and methodology offered in this work can help solar energy system designers understand the distinguishing characteristics among popular MPPT strategies and how improving the design would impact the outcome. It also aims to conduct research into Artificial intelligence methodologies like fuzzy logic, which are projected to be the foundation of future technology.

Pakistan is still inefficient in implementing advanced technologies for efficient utilization of alternative renewable energy resources (Raza et al., 2022b; Wu et al., 2020). Amongst all energy sources, the country is blessed with huge solar potential that can be utilized for power production (R et al., 2022; Raza et al., 2023c). Solar panels are widely available and are fabricated from both P and N-type semiconducting materials (Allouhi et al., 2022; Raza et al., 2023d). The presence of charged carriers in both P and N-type semiconductors causes the creation of an electric field. This electric field then channels electrons from the sunlight hitting the panel's surface, which results in the generation of an electric current (Allouhi et al., 2022; Dahlioui et al., 2022). The PV system development is the necessity for additional elements apart from the solar panel including inverter, battery bank and charge controller (Jackson et al., 2021; Raza et al., 2022e). As the power output supplied by the solar panel is DC power and the required power is AC, it requires electrical equipment such as inverters that convert generated DC power output into AC power. The battery is also needed to store electrical energy (Jackson et al., 2021). Batteries are not required if the PV system is linked to the electrical grid or uses the output power produced directly. The need for batteries arises exclusively when there is a user demand for electricity during night time and the intention to store energy throughout the day for later usage (Du et al., 2020). The PV system presents certain advantages, such as solar panels with affordable operating costs since they are self-contained once installed. Moreover, their maintenance costs are minimal as they are highly resilient and built to endure for many decades (Zimmerman et al., 2020; Rehan et al., 2023). Finally, they are stationary systems with no mechanical movement therefore do not require any kind of lubrication fluids (Zimmerman et al., 2020; Jackson et al., 2021).

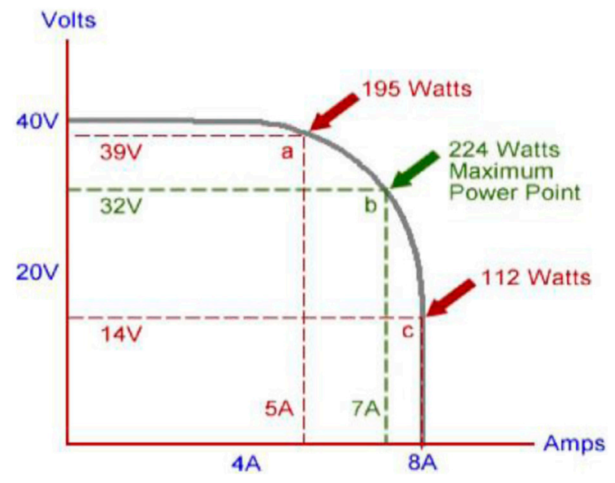

FIGURE 1
Shows maximum power point (Malik et al., 2021).

The MPPT technique is employed to achieve the highest power output during changing weather conditions, the function of MPPT is to keep output power maximum as possible at all the time as shown in Figure 1 (Malik et al., 2021). In the case of energy harvesting from Solar PV system the output power is unpredictable in nature and it is difficult to control. With the help of the appropriate MPPT approach this problem can be resolved. There are several MPPT techniques or algorithms that are being used now days, however, this research will focus specific MPPT algorithms that are ANN, ANFIS, and FLC and their design on MATLAB SIMULINK. To obtain the ideal level of power, all the MPPT methods are employed for discovering the most optimal combination of voltage and current for the panel, ensuring maximum efficiency. The detailed description of these controllers is given below.

1.1 Artificial neural network MPPT

Neural networks and artificial intelligence are data processing systems that draw inspiration from how organic neural systems process the data (Dzung et al., 2016). Intellectual modeling and artificial intelligence aim to imitate certain aspects of biological neural systems (Dzung et al., 2016). Artificial neural networks have proven successful in applications such as speech recognition, image analysis, and adaptive control within the field of artificial intelligence, enabling the development of software applications and automated systems (Fang et al., 2019).

1.2 Fuzzy logic control based MPPT

Fuzzy logics are a subset of many valued logic, they allow a range of values to be considered rather than restricting the results to a binary space. As a result, it may run in the range between "True" and "False" as well as the binary values of 0 and 1, consenting for a more exact representation of the variable (Abbas et al., 2022). The use of linguistic clarification rather than numerical understanding, which brings fuzzy logic nearer to the human thought process, is another distinctive feature (Zhang et al., 2020).

The flexibility of a fuzzy set allows for its customization and adaptation to diverse applications, owing to the incorporation of fuzzy rules within each set. These rules, devised by industry experts based on their expertise, guide the determination of output on basis of input variables (Alcantud et al., 2020; Re et al., 2023). Usually, these rules are structured like conditional statements using logical operators such as "if," "then," "and" "not," and "or." The rules were created in a way that mirror everyday human logic, such as "if " the temperature of area under observation is low, shift the air conditioner to low. "The "IF" and "then" argument was used in this conditioning statement to determine the input and output. In this instance, the room temperature is the input, and the output is level of air conditioner. The last elements of the rule are fuzzy sets that, in this case, reflect input and output values that are both labeled as "low." The control process begins once the mistake and the differences in the values of error are determined. The controller takes the crisp inputs and fuzzifies them by mapping them to linguistic variables associated with their relevant fuzzy set labels. Using the inputs derived by the fuzzifier and fuzzy rules defined by the end-user, the controller's inference engine determines the output choice. The resulting output is subsequently converted by the de-fuzzifier from a linguistic representation to a numeric or crisp value. The shift of duty cycle is necessary for producing output at the MPP that is represented by this integer value (Ali et al., 2023a). The present duty cycle therefore equals to the previous duty cycle adding computed difference to duty cycle.

1.3 Adaptive neural fuzzy inference system MPPT

Similar to a neural network, an ANFIS has layers that are connected to provide the desired results after learning data. Using the fuzzy inference system, the layers in ANFIS are connected (Cho et al., 2020). In terms of the quantity of input and output, ANFIS differs from neural networks. There are restrictions on the input and output data for ANFIS. In ANFIS there are two inputs and one output X, Y and F. The ANFIS system uses Sugeno inference system which is divided into two parts one is antecedent part (IF part) and the second part is consequent (THEN part) (Habib et al., 2022).

The goal of the ANFIS is to create a hybrid system which combines the fuzzy logic theory with a neural network map to minimize challenges and integrate benefits (Abdelkader et al., 2022). The ANFIS controller needs data for training. This training data is dependent on the ANFIS-integrated system (Mohammed et al., 2021). The PV panel and ANFIS controller are connected in our system. These training data sets are generated under arbitrary operating parameters within a predetermined range. Therefore, it includes every scenario that could possibly occur throughout the day the voltage that is supplied the most power under these weather conditions is then stored (Subha et al., 2021; Habib et al., 2022).

2 Related works

The efficiency of MPPT algorithms can be affected by a number of factors, including the environmental conditions, the specifications of the solar panel, and the architecture of the algorithm itself. These challenges make it difficult to determine which MPPT algorithm is the most optimal for a given application. In some cases, algorithm designers may not take into account all of these factors, that can lead to failure in some working situations. The nonlinear behavior of the PV system is considered to be its main characteristic (Ali et al., 2023b; Motahhir et al., 2020). The ratio of the change in voltage to the change in current at a specific operating point is referred as the dynamic resistance of a solar module. It is a measure of how quickly the voltage across the module changes in response to a change in current (Ahm et al., 2023). As a result, the MPPT algorithm can more easily identify the maximum power point in these regions where the dynamic resistance is essentially constant (Fares et al., 2021). The MPPT controller in the power region needs to be modified in light of this phenomenon. The power and voltage characteristics of the PV panel are used in conventional MPPT techniques like perturb and observe and incremental conductance (Cho et al., 2020). The algorithm perturbs the PV panel's voltage in the perturb and observe approach while tracking changes in current. The dynamic resistance is then determined by dividing the voltage change by the current change. After the maximum power point is reached, however, this technique may result in steady-state oscillations, which may increase the loss of power (Sundararaj et al., 2020).

Under any temperature and insolation conditions, the voltage of a photovoltaic (PV) module typically varies between 70% and 80% of its open-circuit voltage (Voc). This indicates that a PV module's maximum power point (MPP) usually falls within this range (Villegas-Mier et al., 2021). However, this approach is only appropriate in areas with minimal temperature change. This is because the temperature impacts the Imp-Iph relationship, and if the temperature varies widely, the relationship will not be correct (Nassef et al., 2022). The duty cycle, or ratio of the converter's ON time to its OFF time, determines how efficient a DC-DC converter is. The input voltage and the output voltage both have an impact on efficiency. Another crucial factor is the converter's settling time, which governs how quickly the converter may attain its steady-state output voltage (Ali et al., 2023c). MPPT algorithms use voltage and current sampling to determine power at each step. The direction of tracking is then determined by this power for MPPT algorithms like the perturb and observe approach and for more sophisticated techniques (Seguel et al., 2022). The measured values of the voltage and current will be erroneous if the step size of the MPPT algorithm is smaller than

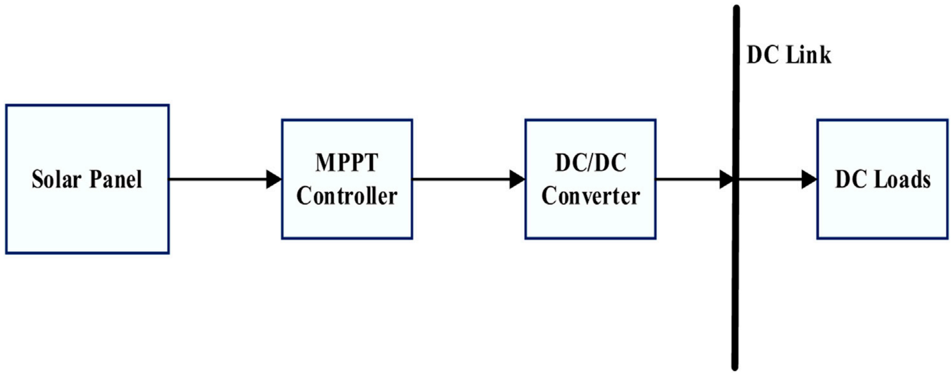

FIGURE 2
Depicts the solar PV system connected to MPPT controller.

TABLE 1 Shows the solar PV model specifications (Ali et al., 2023d).

S.No	Data	Value
1	Maximum power	248.9 W
2	Cells per module	60
3	Open circuit voltage (Voc)	30.7 V
4	Short circuit current (Isc)	8.85 A
5	Voltage at MPP (Vmp)	30.7 V
6	Current at MPP (Imp)	8.11 A
7	Temperature coefficient of Voc	−0.35599

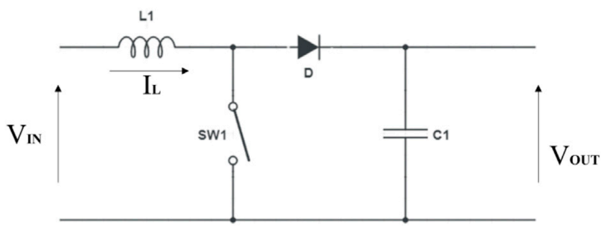

FIGURE 3
Shows the construction of a DC-DC converter (Srinivasan et al., 2021).

the converter's settling time, which will result in improper tracking of the PV curve (Hanzaei et al., 2020). A PV module's current and voltage are regulated in relation to the maximum power point using the controller duty cycle. Instability may result if the controller design is not thoroughly thought out (Hanzaei et al., 2020).

Numerous studies have been carried out to evaluate the effectiveness of different MPPT algorithms. For instance, in (Pattnaik et al., 2021), an adaptive ANFIS algorithm based MPPT controller was introduced that eliminates the requirement for additional sensors to calculate illumination and the temperature.

TABLE 2 Shows the ratings of components (Srinivasan et al., 2021).

S:NO	Component	Rating
1	Resistor	57.6000
2	Inductor	1e-03
3	Capacitor	1.2920e-04

The effectiveness of the proposed ANFIS-MPPT technique was validated on MATLAB simulink, outperforming the conventional incremental conductance based MPPT technique. Another study (Osman et al., 2022) worked on designing an efficient MPPT controller for PV systems using an ANFIS. A multi-variable step perturb and observe approach was used to collect data precisely in order to train the ANFIS model. The ANFIS-MPPT controller demonstrated superior performance in comparison to perturb and observe and FLC approaches ensuring efficient tracking of the optimal power point under various environmental conditions. Furthermore (Mirsaeidi et al., 2023), proposed an ANFIS-based MPPT controller for optimizing PV systems. The controller effectively tracked the maximum power point of a 400 W PV module connected with a DC-DC converter, showcasing dynamic response and efficiency. Additionally (Al-Majidi et al., 2019a), presented an ANFIS-MPPT method trained on extensive experimental training data, achieving accurate tracking of the maximum power point with efficiencies exceeding 99.3%. Another study (Ibrahim et al., 2021) employed ANFIS for partial shading conditions, resulting in an impressive efficiency of 99.92%. Various research works have investigated the performance of Artificial Intelligence AI based MPPT algorithms.

Furthermore (Al-Majidi et al., 2019b), presents an ANN-based MPPT approach for PV systems using extensive experimental training data. The suggested technique achieves accurate tracking of the peak power point and yields higher output power comparing to the perturb and observe controller. In a similar study (Hashim et al., 2021), a hybrid method is proposed which combines an ANN with other techniques to address the reduction in peak power caused by partial shading in PV panels. Simulations in MATLAB are conducted to assess the effectiveness of the suggested technique

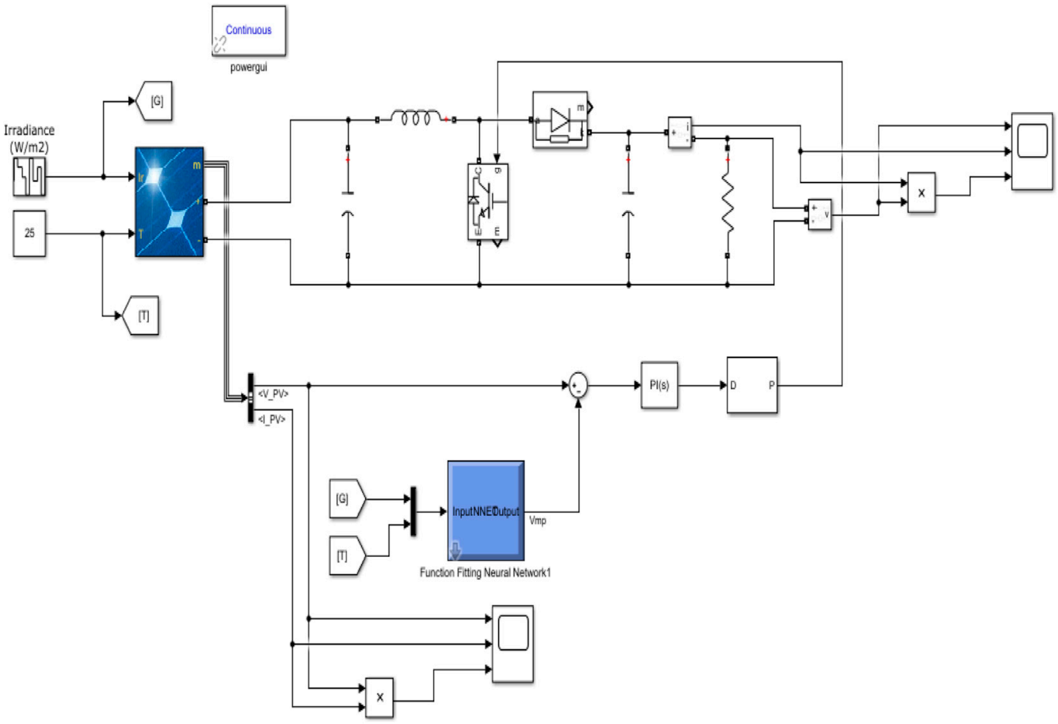

FIGURE 4
Shows Simulink model of ANN MPPT.

in comparison to other strategies. Additionally, analysis of current, voltage, and power characteristics aids in determining optimal settings. FLC based MPPT methods have also been explored. In (Abbas et al., 2023), an MPPT method using fuzzy logic control for stand-alone PV systems is presented. The results demonstrate the outperformance of the FLC in comparison to the conventional perturb and observe technique, especially under varying weather conditions. Another study (Singh et al., 2023) reviews the MPPT control strategies currently in use and suggests a unique adaptive fuzzy-based MPPT strategy for PV systems. When compared to traditional methodologies, the proposed scheme performs better in terms of speed, smoothness, and computing efficiency. The combination of teaching-learning (TL) and artificial bee colony (ABC) called TLABC are hybridized in this (Kishore et al., 2023a) work for mitigating the oscillations around the GMPP. To find the effectiveness of the proposed method, it can be evaluated with other methods such as PSO, IGWO, MFO, and SSA. As per simulation outcomes, the proposed TLABC shows greater performance in terms of Standard Deviation (SD), Mean Absolute Error (MAE), Successful rate (Suc. Rate), and efficiency are 3.95%, 0.13%, 98.88% and 99.89% respectively. In another study (Jan et al., 2022), a hybrid approach combining gray wolf optimization (GWO) and differential evolution (DE), referred to as GWO-DE, is employed to track the global maximum peak power (GMPP) in photovoltaic systems, as opposed to local maxima peak power (LMPP). The system is implemented using MATLAB/Simulink software and evaluated under various atmospheric conditions, with performance comparisons against other existing methods. Simulation results demonstrate that the GWO-DE hybrid approach outperforms other methods in terms of convergence time, accuracy, extracted power, and efficiency. Experimental development and testing in four different cases reveal GMPP outcomes ranging from 602.56 to 984.65 W, further confirming the superiority of the proposed hybrid GWO-DE method over other studied approaches. The other study in (Kishore et al., 2023b) addresses the challenge of maximizing peak power in photovoltaic (PV) systems, particularly in the presence of partial shading conditions (PSC), which can introduce nonlinearity. Traditional approaches have shown oscillations in achieving global maximum peak power (GMPP). To overcome this issue, the study introduces a novel metaheuristic method, the opposition-based equilibrium optimizer (OBEO) algorithm. The OBEO algorithm is compared with other methods like SSA, GWO, and P&O. Simulation results reveal that the OBEO method outperforms other methods, achieving an efficiency of 95.09% under dynamic PSC in 0.16 s, 96.17% under uniform PSC, and 86.25% under complex PSC, demonstrating its effectiveness in mitigating oscillations around GMPP in PV systems.

Existing research on intelligent MPPT controllers has mostly focused on comparing the performance of different algorithms under ideal conditions. However, real-world PV systems operate under a variety of conditions, including varying irradiance and temperature. This study addresses this gap by conducting a comprehensive comparative analysis of ANN, ANFIS, and FLC MPPT controllers under real-world scenarios. In addition, this study provides quantitative results on the performance of the three controllers under varying irradiance conditions. This information is valuable for solar energy system designers and consumers in selecting the most suitable MPPT controller for their specific needs. Furthermore, this study

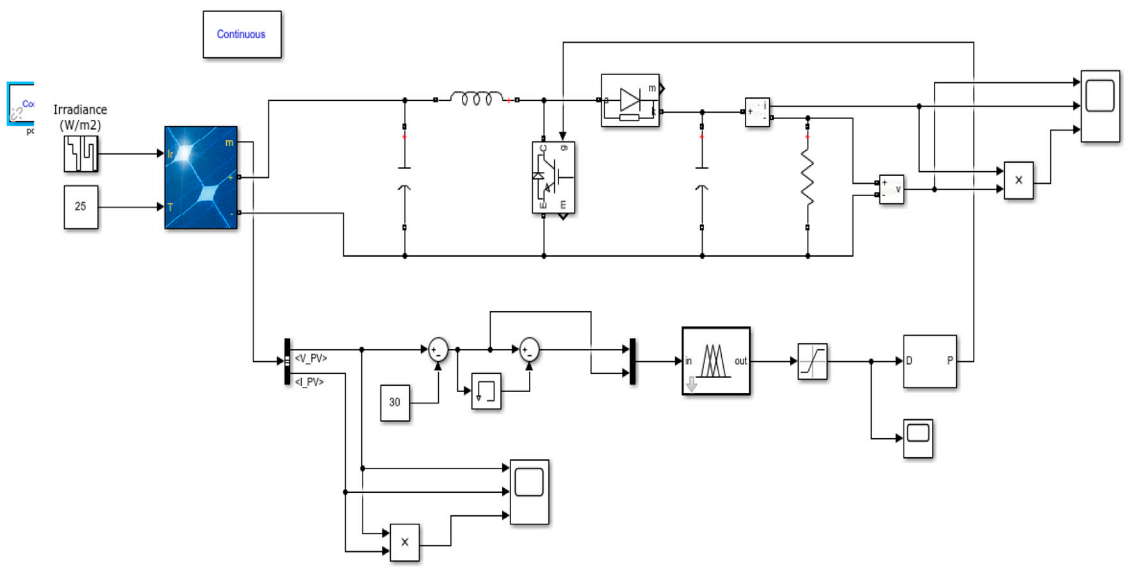

FIGURE 5
Shows Simulink model of ANFIS MPPT.

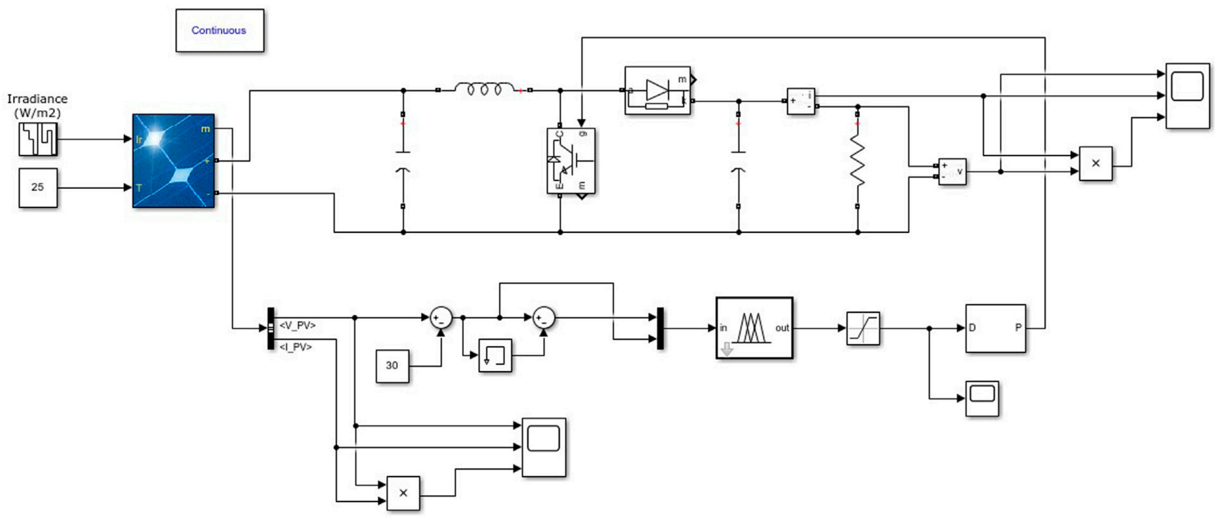

FIGURE 6
Shows the Simulink model of FLC MPPT.

investigates how temperature and irradiance affect the power output of a PV solar array. This information is important for understanding the performance of PV systems under different operating conditions.

3 Research methodology

The research flow diagram is depicted in Figure 2. The arrangement of MPPT PV system is designed under the varying solar irradiance using the MATLAB Simulink. The basic blocks contain solar panel that is connected with the MPPT controller and DC to DC boost converter for boosting up the voltage. One common standalone system is created then different MPPT techniques such as ANN, ANFIS and FLC are applied on the designed standalone system. The description of each component of block diagram is given below.

3.1 Photovoltaic (PV) module

PV technology encompasses various forms in this study, the mono-crystalline silicon cell was chosen due to its exceptional efficiency. The 1Soltech 15TH–FRL-4H-250-M60-BLK solar module was selected for this design and its specifications are given in Table 1 (Ali et al., 2023d). When it concerns solar panel

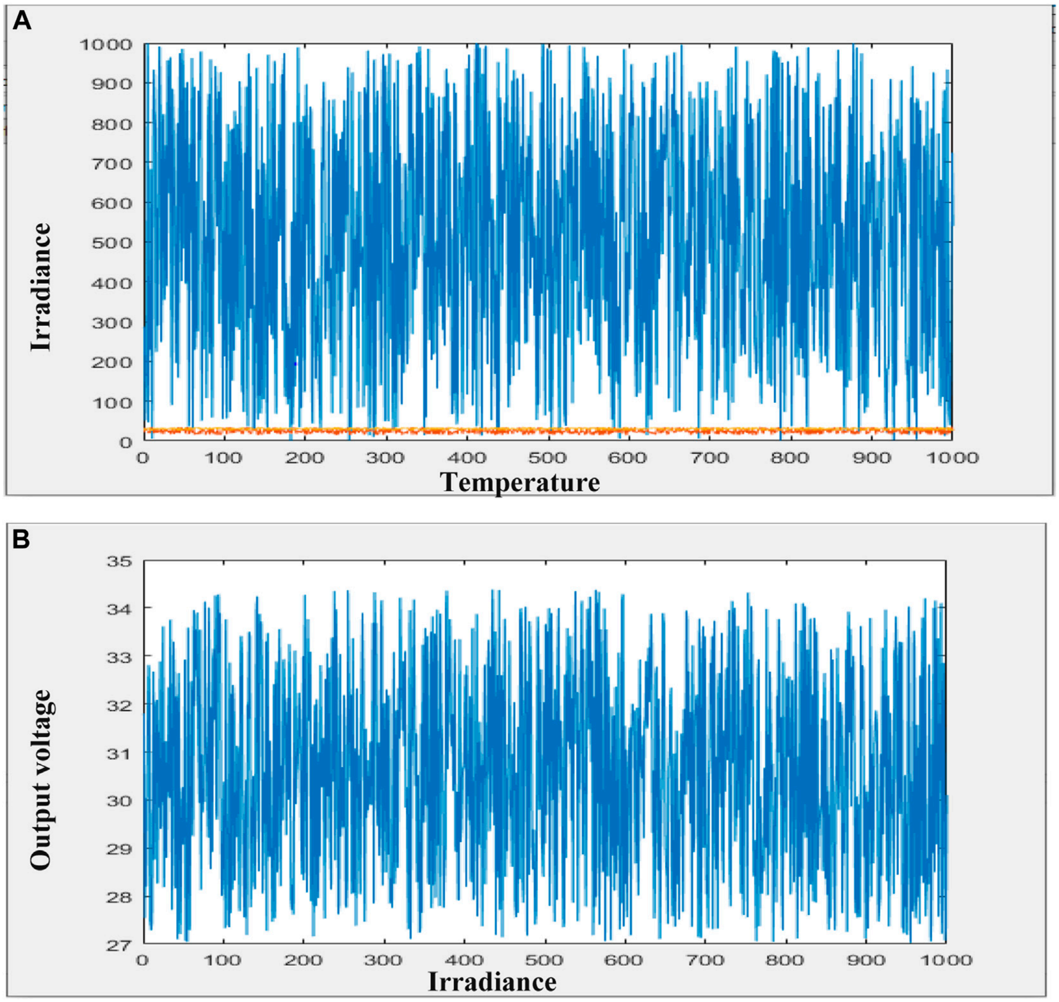

FIGURE 7
(A) Input values of temperature and irradiance. **(B)** Depicts the output voltage data for different values of irradiance.

TABLE 3 Shows the input values of temperature and irradiance over time.

Time range (sec)	Irradiance value (W/m^2)	Temperature value (°C)
0–0.2	200	25
0.2–0.4	400	25
0.4–0.6	600	25
0.6–0.8	800	25
0.8–1.0	1,000	25

performance, Sun power is a distinguished manufacturer that stands among the top contenders in the industry.

3.2 DC-DC converter

In this work, a specific type of DC-DC converter called boost converters was used. The boost converter reduces output current by raising output voltage which lowers the current's thermal losses. The fundamental parts of a boost converter are illustrated in Figure 3, including a diode, a switch, and an energy storing unit (Srinivasan et al., 2021). Typically, an inductor serves as the energy storage component and an insulated gate bipolar transistor (IGBT) is utilized as a switch. The ratings for components of boost converter are mentioned below in Table 2 (Srinivasan et al., 2021).

3.3. MPPT controllers design

In this study, three distinct Maximum Power Point Tracking (MPPT) methods were developed using MATLAB Simulink. The MPPT can be implemented either through coding or by constructing a Simulink model utilizing various blocks. This research proposal aims to explore these approaches. The MATLAB Simulink model has been created for each Maximum Power Point Tracking (MPPT) controller, namely, Artificial Neural Network (ANN), Adaptive Neuro-Fuzzy Inference System (ANFIS), and Fuzzy Logic Controller (FLC), in relation to a typical solar photovoltaic (PV) system. The irradiance is maintained within the range of

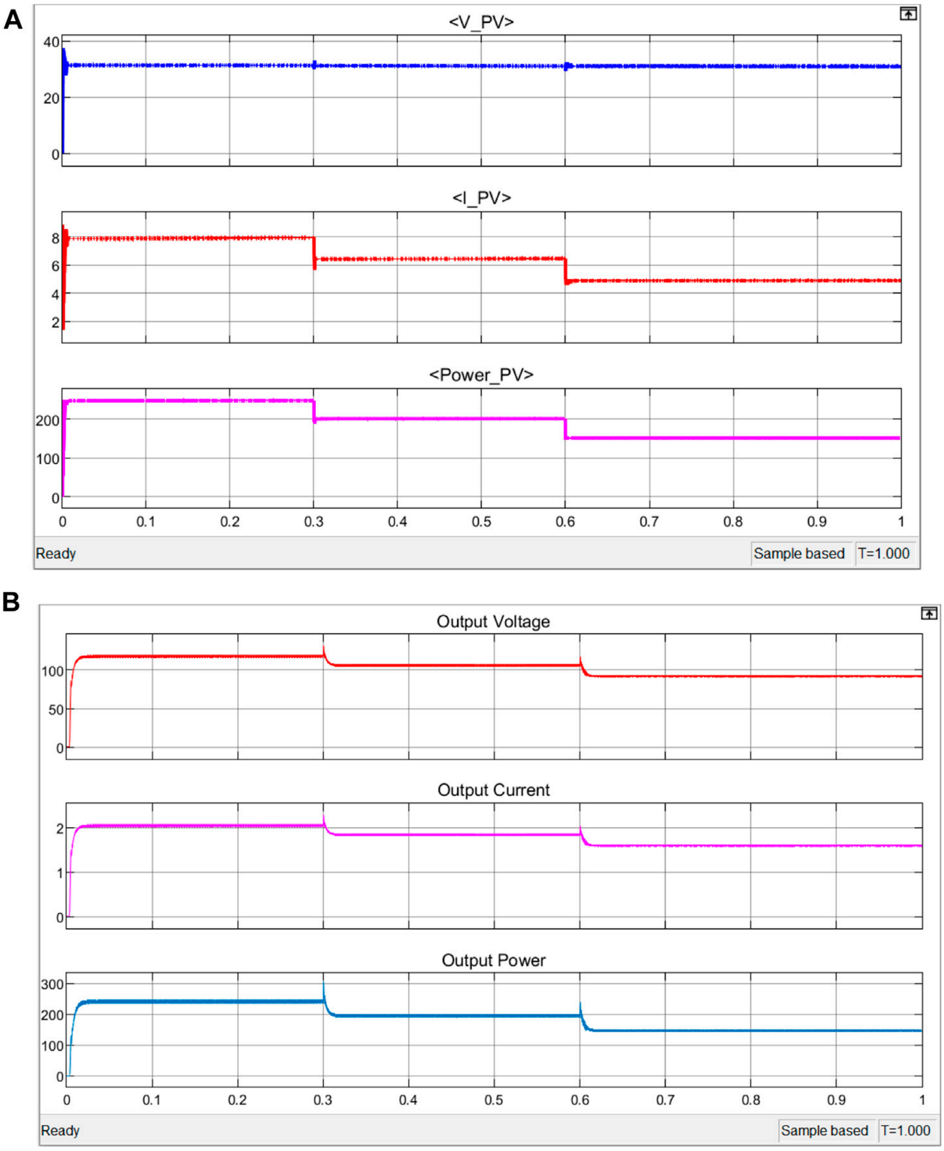

FIGURE 8
(A) MPPT input power, voltage, and current signals. **(B)** ANN MPPT output for power, voltage, and current signals.

TABLE 4 Shows the power extraction by ANN at specified temperature and irradiance w.r.t time instant.

Time instant (seconds)	Irradiance value (W/m^2)	Temperature value (°C)	Actual output power (W)	Theoretical output power (W)	Efficiency (%)
0–2	1,000	25	242.60	250	97.04
2–4	800	25	193.80	200	96.90
4–6	600	25	140.82	150	93.88

200–1,000 W/m^2 at a temperature of 25°C, in accordance with a constant.

The design of our Artificial Neural Network (ANN) Maximum Power Point Tracking (MPPT) system involved setting up a standalone PV system. The Standalone system includes a solar panel, a boost converter (to raise the voltage from 30 to 120 V for optimal power output), and an electrical load. An additional PI controller is used with ANN MPPT to improve its robustness, adaptability to real-world conditions, dampen oscillations, enhance tracking accuracy, and ensure compatibility with existing systems. Additionally, to have accurate training data for ANN, the data is generated using MATLAB programming, based on the solar

TABLE 5 Shows the maximum power extracted by all three MPPTs at specified temperature and irradiance.

Technique	Irradiance value (W/m^2)	Temperature value (°C)	Extracted output power (W)	Theoretical output power (W)	Efficiency (%)
ANN	1,000	25	242.6	250	97.04
FLC	1,000	25	246.3	250	98.50
ANFIS	1,000	25	248.2	250	99.50

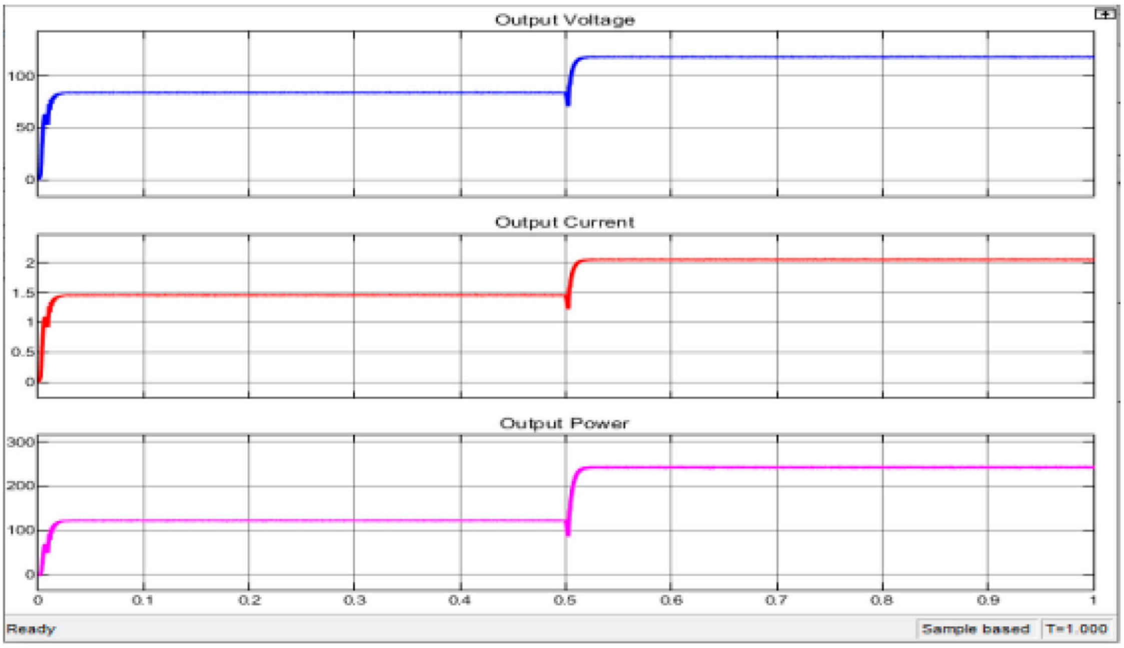

FIGURE 9
FLC MPPT output for voltage, current and power signals.

panel's characteristics. After the model is trained, the ANN block is integrated into the PV system as shown in Figure 4. Finally, the ANN-based MPPT is tested on the system under changing levels of irradiance that mimic the real environmental conditions. This testing aimed to show how well the ANN MPPT system works, how it adapts to different conditions, and how easily it can be controlled, giving us a clear picture of its performance.

The design and implementation of the Adaptive Neural and Fuzzy Inference System (ANFIS) Maximum Power Point Tracking (MPPT) system were conducted within a standalone configuration, encompassing a photovoltaic (PV) panel, a boost converter, and an electrical load. In addition to the ANFIS, a Proportional-Integral (PI) controller was incorporated into the system design to enhance stability and performance. Subsequently, training data were generated through MATLAB programming, leveraging the intrinsic characteristics of the PV panel. Following the training phase, the trained ANFIS model was deployed within the PV system. Subsequent evaluations were undertaken under varying real-world environmental conditions to elucidate the ANFIS MPPT system's operational efficiency, adaptability to dynamic conditions, and controllability, providing comprehensive insights into its functionality and suitability for practical applications. The design of ANFIS MPPT is depicted in Figure 5.

Fuzzy Logic Controller (FLC) for Maximum Power Point Tracking (MPPT) designed in MATLAB, utilizes the same standalone photovoltaic (PV) system employed for evaluating ANN and ANFIS controllers. This design process involves the initialization of membership functions for key variables, including voltage, current, and power, followed by the implementation of these functions using the Fuzzy Logic block within MATLAB Simulink. Additionally, memory blocks have been integrated into the FLC model to store and access historical voltage values, enhancing control strategies that depend on past system states as shown in Figure 6.

4 Results and discussion

The irradiance was changed from 200 W/m2 to 1000 W/m2 and the temperature maintained constant at 25 °C and this method is adopted to analyze the individual effects of each variable on the power output. Table 3 summarizes these distinct periods, each

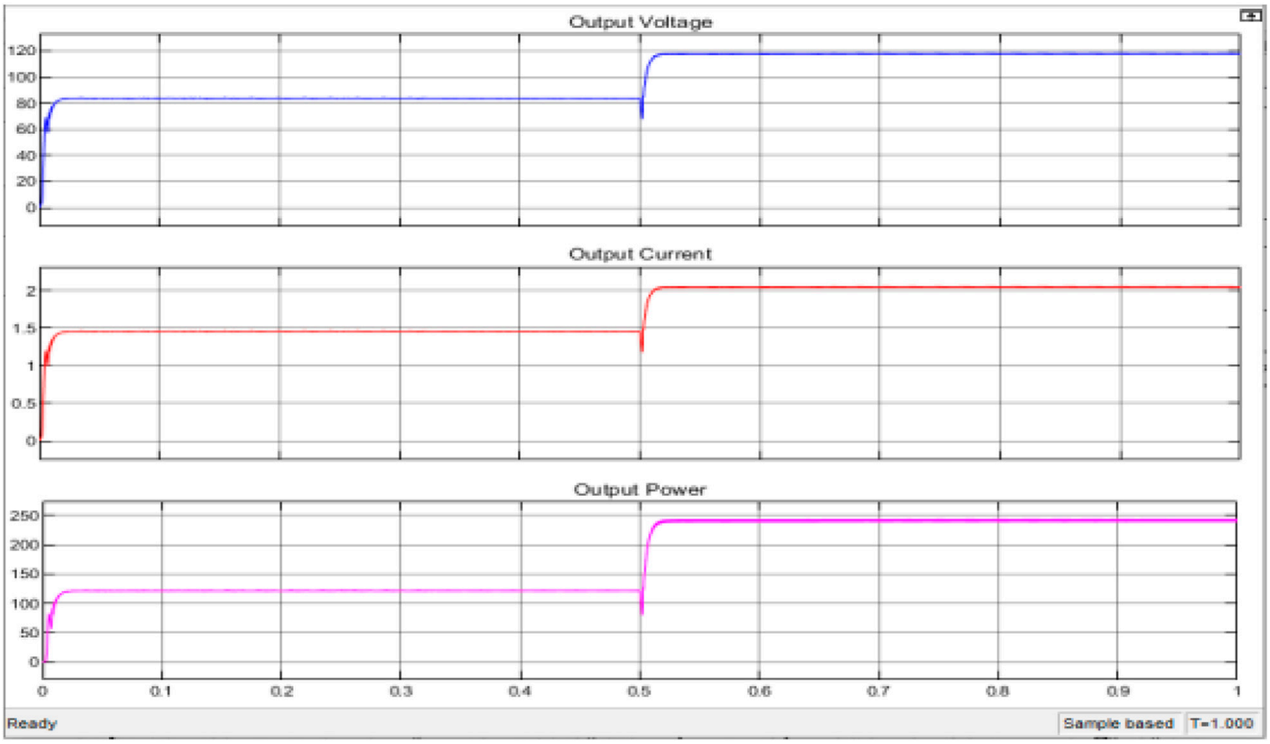

FIGURE 10
ANFIS MPPT output for voltage, current and power signals.

corresponding to variation in irradiance under constant temperature conditions expressed as a time step of 0.2 s.

4.1 Implementation of artificial neural network on solar PV system

In this setup the current, voltage and power values are calculated at MPP by taking the value of temperature as 25 ˚C for varying irradiance from 1,000 to 200 W/m2. The input data consisting varying irradiance and temperature values for training the ANN MPPT are generated by the use of MATLAB programming by employing the panel specifications as shown in Figure 7A. Similar to the inputs, output voltage is calculated with respect to irradiance and temperature. The output data is shown in Figure 7B.

On the implementation of specified irradiance and temperature conditions the PV panel generates voltage, current and power based on its characteristics as shown in Figure 8A. The outputs of the PV panels are more weather dependent, and they greatly vary under varying conditions, therefore the MPPT is aimed to continuously maintain these outputs. As in this case, the output voltage of the PV panel is compared with the output voltage from the ANN MPPT controller which leads to the generation of signal given to the pulse generator to calculate the sufficient duty cycle for the IGBT switch to maintain the desired outputs. The IGBT switch according to the generated duty cycle boost up the PV panel's output voltage from 30 to 120 V. In the provided Figure 8B, the output power curve demonstrates a gradual rise at the beginning reaching a peak of 242.60 W, corresponding to an irradiance value of 1,000 W/m^2 and a constant temperature of 25 ˚C. Subsequently, in the second phase, while maintaining a constant temperature, the output power declines to approximately 200.80 W when the irradiance drops to 800 W/m^2. Moving to the third phase, the irradiance further decreases to 600 W/m^2, resulting in a output power of 145.62 W as shown in Table 4.

4.2 Implementation of fuzzy logic controller on solar PV system

In this case, we conducted assessments using the Fuzzy Logic Controller (FLC) algorithm on a PV system, focusing on current, voltage, and power measurements at the Maximum Power Point (MPP). In this specific case of FLC, the controllers' effectiveness is assessed under specific conditions, including an operating temperature of 25 ˚C and sudden variations in solar irradiance, and the overall simulation duration lasted 1 s. During the initial half-second interval, from 0 s to 0.5 the irradiation is 200 W/m^2 thus producing an output power of 140 W and during the second instant, the irradiance rapidly increases from 200 W/m^2 to 1,000 W/m^2 which produces an output power of around the 246.3 W as shown in Figure 9. As the irradiance varies there is also a variation in the voltage and current of the FLC PV controller and converter. With regards to the response of the panel voltage and current, the current experiences a substantial effect caused by a decline in irradiance. However, there appears to be minimal effect on the PV voltage from either adjustment, while its response is primarily influenced by the temperature, which is held constant at 25°C. When the irradiances vary, the duty cycle also fluctuates from 0.6 to 0.5. These small fluctuations in the duty cycle highlight the controllability of the FLC algorithm.

4.3 Implementation of adaptive neural and fuzzy inference system on solar PV system

In case of ANFIS MPPT controller the output is being carried with a sudden increase in radiation exposure. The temperature during this remains constant at 25 °C. Figure 10 demonstrates that the irradiation level is steady at 200 W/m^2 for the first 0.5 s before rapidly increasing to 1000 W/m^2 in next 0.5 s. The power values extracted by ANFIS MPPT alter in accordance with the level of radiation. The PV panel produces more power when the level of irradiation is higher. The highest power the ANFIS MPPT could extract at the temperature of 25 °C and an irradiation of 200 W/m^2 is roughly 130 W while in the second instant when the PV panel's irradiance changes to 1,000 W/m^2 its maximum output power of 248.2 W is extracted. As the irradiance changes there is also a variation in the current, power and voltage of the ANFIS PV controller showing that it accurately maintains the power corresponding to the variations as shown in Figure 10.

5 Comparative analysis of intelligent controller for photovoltaic system

A comparative performance analysis of different MPPT techniques was conducted in terms of irradiance, operational and MPP tracking efficiency. The fundamental goal of the MPPT algorithm is to track the MPP at variable solar irradiation. The choice of a suitable MPPT technique is a challenging decision. ANFIS control demonstrates notable efficiency with faster response and high tracking accuracy as shown in Table 5. In the past few years, there has been a potential enhancement in MPPT studies due to their use in many applications. This paper evaluated a number of articles on MPPT techniques. Therefore, it is difficult to clearly choose the best algorithm. The desired MPPT algorithm can easily be chosen on the basis of its application and each controller's specification. The cost of designing the controllers is another important factor that could be used to compare MPPT algorithms. In general, controllers utilize many devices in their design, which vary based on their intended application and sensitivity. These factors can have a substantial impact on the overall cost associated with controller design. However, it is important to acknowledge that as the complexity of the computation and execution of MPPT algorithms increases, so does the associated cost. Based on the classification outlined in this study, the expenses related to the development and execution of algorithms escalate as one progresses from basic to more sophisticated levels.

A review was done of the number of articles that particularly examined each of the three different types of MPPT controllers (measurement-based methods, calculation-based methods, intelligent schemes, and hybrid schemes). This is based on the general data on the volume of articles published during the last 10 years that was provided in this paper's introduction and literature review section. It has been found that recent research has concentrated on intelligent and hybrid algorithms. This is due to the limitations of conventional algorithms and the inherent nature of MPPT systems' partial shading problem. Intelligent algorithms have been able to make significant changes in any field that they have been introduced to. Additionally, by mixing algorithms, the benefits of both approaches can be utilized to produce more accurate results with fewer drawbacks. Another important factor which needs to be considered for MPPT control systems is their integration with system and the complications associated with it. While it is critical to improve existing algorithms and introduce new ones in order to maximize system efficiency, implementation simplicity is as crucial. Some of the variables that need to be taken into account include high costs, complex designs, the presence of additional hardware, and ultimately, implementation challenges. Traditional algorithms that are not extremely difficult to create and implement include the perturbation and observation controller. But the adoption of clever techniques also presented difficulties. The adoption of these techniques raises the cost of the control system overall by adding more hardware. The control system confronts difficulties in the actual world due to the need for extra hardware, design complexity, and rising implementation costs, among other factors.

To conclude, the decision on the optimal MPPT algorithm is influenced by multiple factors, including the application, the cost, the complexity, and the ease of implementation. Traditional algorithms stand as an appropriate choice for applications where cost and complexity are important considerations. Intelligent and hybrid algorithms stand as an appropriate choice for applications where accuracy is important, even in the presence of challenging environmental conditions.

6 Benefits and drawbacks of MPPT solar controller

Following are the potential advantages or strengths of using MPPTs for solar PV systems (Giurgi et al., 2022; Hadj Salah et al., 2023).

- They are more efficient as compared to PWM generator.
- MPPT can offer DC load optimization and can optimize voltage differences.
- They are the best choice for large scale PV systems where output of solar PV panel is substantially higher than battery voltage.
- They offer greater output and hence greater capacity (Amp).
- Following are the drawbacks or disadvantages of MPPT solar PV systems (Basha and Rani, 2020; Rafikiran et al., 2023).
- They are more costly when compared to conventional PWM based solar charge controller.
- Their larger size makes them challenging to handle.
- Use of more electronic components and more thermal stress causes MPPTs have shorter lifespan.

7 Conclusion and future work

This research aims to offer decision-makers and solar energy consumers a comprehensive understanding of the principles behind MPPT, the various factors that impact it, and methods to optimize its performance. With this being said, following were said to be the fundamental goals of this work: to evaluate the capability of several controllers to track their maximum power under varying irradiance conditions and under both stable and unstable weather situations such as varying irradiance and constant temperature values. To investigate how a PV solar array's power output is affected by temperature and irradiance. For this purpose, three controllers were used in this study that are: Artificial Neural Network (ANN), Fuzzy Logic Controller (FLC) and Adaptive neural and Fuzzy Inference System (ANFIS). These controllers were designed and simulated by using the MATLAB Simulink. These procedures were simulated with variable irradiance levels and constant temperatures. The analysis and methodology offered in this work can help solar energy system designers to understand the distinguishing characteristics among popular MPPT strategies and how improving the design would impact the outcome. It also aims to conduct research into Artificial intelligence methodologies like fuzzy logic, which are projected to be the foundation of future technology.

In forthcoming research, the evaluating range for environmental temperatures below 25 °C and above 50 °C should be expanded as various regions of the world, including few countries in the Europe and Middle East, experience these temperatures. Studying the impact of simultaneously adjusting the temperature and irradiance is another important consideration. This may happen in some circumstances. Another suggestion is to utilize more rules in FLC and investigate the impact on tracking efficiency. One other idea for future work is to make the necessary adjustments and link the standalone PV system to the grid in order to assure a more precise depiction of the real electrical power generated.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MK: Conceptualization, Writing–original draft. MR: Conceptualization, Writing–original draft. TJ: Conceptualization, Methodology, Writing–original draft, Writing–review and editing. SM: Funding acquisition, Project administration, Supervision, Validation, Writing–original draft. AaA: Writing–review and editing, Validation. GA: Formal Analysis, Validation, Writing–original draft, Writing–review and editing. ET: Formal Analysis, Project administration, Supervision, Writing–review and editing. AhA: Data curation, Investigation, Software, Writing–original draft.

Funding

The authors declare financial support was received for the research, authorship, and/or publication of this article. This work was supported in part by the National Natural Science Foundation of China under Grant 52150410399, in part by the Beijing Natural Science Foundation under Grant IS23051, and in part by the Fundamental Research Funds for the Central Universities under Grant 2019RC051.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abbas, G., Ali, B., Chandni, K., Koondhar, M. A., Chandio, S., and Mirsaeidi, S. (2022). A parametric approach to compare the wind potential of sanghar and gwadar wind sites. *IEEE Access* 10, 110889–110904. doi:10.1109/ACCESS.2022.3215261

Abbas, G., Bhutto, A. A., Jumani, T. A., Mirsaeidi, S., Tunio, M. A., Alnuman, H., et al. (2023). A modified particle swarm optimization algorithm for power sharing and transient response improvement of a grid-tied solar PV based A.C. Microgrid. *C. Microgrid. Energies.* 16 (1), 348. doi:10.3390/en16010348

Abdelkader, A. B., Mouloudi, Y., and Soumeur, M. A. (2022). Integration of renewable energy sources in the dynamic voltage restorer for improving power quality using ANFIS controller. *Journal of King Saud University-Engineering Sciences.*

Ahmed, M. A., Abbas, G., Jumani, T. A., Rashid, N., Bhutto, A. A., and Eldin, S. M. (2023). Techno-economic optimal planning of an industrial microgrid considering integrated energy resources. *Front. Energy Res.* 11, 1–12. doi:10.3389/fenrg.2023.1145888

Alam, P., Sharholy, M., Khan, A. H., Ahmad, K., Alomayri, T., Radwan, N., et al. (2022). Energy generation and revenue potential from municipal solid waste using system dynamic approach. *Chemosphere* 299, 134351. doi:10.1016/j.chemosphere.2022.134351

Alcantud, J. C. R., Khameneh, A. Z., and Kilicman, A. (2020). Aggregation of infinite chains of intuitionistic fuzzy sets and their application to choices with temporal intuitionistic fuzzy information. *Inf. Sci.* 514, 106–117. doi:10.1016/j.ins.2019.12.008

Ali, A., Abbas, G., Keerio, M. U., Koondhar, M. A., Chandni, K., and Mirsaeidi, S. (2023b). Solution of constrained mixed-integer multi-objective optimal power flow problem considering the hybrid multi-objective evolutionary algorithm. *IET Gener. Transm. Distrib.* 17 (1), 66–90. doi:10.1049/gtd2.12664

Ali, A., Abbas, G., Keerio, M. U., Mirsaeidi, S., Alshahr, S., and Alshahir, A. (2023a). Multi-objective optimal siting and sizing of distributed generators and shunt capacitors considering the effect of voltage-dependent nonlinear load models. *IEEE Access* 11, 21465–21487. doi:10.1109/ACCESS.2023.3250760

Ali, A., Abbas, G., Keerio, M. U., Mirsaeidi, S., Alshahr, S., and Alshahir, A. (2023d). Pareto front-based multiobjective optimization of distributed generation considering the effect of voltage-dependent nonlinear load models. *IEEE Access* 11, 12195–12217. doi:10.1109/ACCESS.2023.3242546

Ali, B., Abbas, G., Memon, A., Mirsaeidi, S., Koondhar, M. A., Chandio, S., et al. (2023c). A comparative study to analyze wind potential of different wind corridors. *Energy Rep.* 9, 1157–1170. doi:10.1016/j.egyr.2022.12.048

Allouhi, A., Rehman, S., Buker, M. S., and Said, Z. (2022). Up-to-date literature review on Solar PV systems: technology progress, market status and R&D. *J. Clean. Prod.* 362, 132339. doi:10.1016/j.jclepro.2022.132339

Al-Majidi, S. D., Abbod, M. F., and Al-Raweshidy, H. S. (2019a). Design of an efficient maximum power point tracker based on ANFIS using an experimental photovoltaic system data. *Electronics* 8 (8), 858. doi:10.3390/electronics8080858

Al-Majidi, S. D., Abbod, M. F., and Al-Raweshidy, H. S. (2019b). Design of an intelligent MPPT based on ANN using a real photovoltaic system data 54th international universities power engineering conference (UPEC). 3-6 Sept. 2019, China, IEEE.

Awan, M. M. A. (2022). Technical review of MPPT algorithms for solar photovoltaic system: SWOT analysis of MPPT algorithms. *Sir Syed Univ. Res. J. Eng. Technol.* 12 (1), 98–106. doi:10.33317/ssurj.433

Basha, C. H., and Rani, C. (2020). Design and analysis of transformerless, high step-up, boost DC-DC converter with an improved VSS-RBFA based MPPT controller. *Int. Trans. Electr. Energy Syst.* 30 (12), e12633. doi:10.1002/2050-7038.12633

Chou, K.-Y., et al. (2020).Adaptive neuro fuzzy inference system based MPPT algorithm applied to photovoltaic systems under partial shading conditions, International Automatic Control Conference (CACS), October 15, 2022, USA. IEEE.

Dahlioui, D., Laarabi, B., and Barhdadi, A. (2022). Review on dew water effect on soiling of solar panels: towards its enhancement or mitigation. *Sustain. Energy Technol. Assessments* 49, 101774. doi:10.1016/j.seta.2021.101774

Du, J., Tian, J., Wu, Z., Li, A., Abbas, G., and Sun, Q. (2020). An interval power flow method based on linearized DistFlow equations for radial distribution systems. *Asia-Pacific Power Energy Eng. Conf. APPEEC.* 2020-September, 3–7. doi:10.1109/APPEEC48164.2020.9220372

Dzung, P. Q., Lee, H. H., and Vu, N. T. D. (2016). "The new MPPT algorithm using ANN-based PV," in *International forum on strategic technology* (Germany: IEEE).

Fang, W., Chao, F., Yang, L., Lin, C. M., Shang, C., Zhou, C., et al. (2019). A recurrent emotional CMAC neural network controller for vision-based mobile robots. *Neurocomputing* 334, 227–238. doi:10.1016/j.neucom.2019.01.032

Fares, D., Fathi, M., Shams, I., and Mekhilef, S. (2021). A novel global MPPT technique based on squirrel search algorithm for PV module under partial shading conditions. *Energy Convers. Manag.* 230, 113773. doi:10.1016/j.enconman.2020.113773

Giurgi, G.-I., Szolga, L. A., and Giurgi, D.-V. (2022). Benefits of fuzzy logic on MPPT and PI controllers in the chain of photovoltaic control systems. *Appl. Sci.* 12 (5), 2318. doi:10.3390/app12052318

Habib, S., Abbas, G., Jumani, T. A., Bhutto, A. A., Mirsaeidi, S., and Ahmed, E. M. (2022). Improved whale optimization algorithm for transient response, robustness, and stability enhancement of an automatic voltage regulator system. *Energies* 15 (14), 5037. doi:10.3390/en15145037

Hadj Salah, Z. B., Krim, S., Hajjaji, M. A., Alshammari, B. M., Alqunun, K., Alzamil, A., et al. (2023). A new efficient cuckoo search MPPT algorithm based on a super-twisting sliding mode controller for partially shaded standalone photovoltaic system. *Sustainability* 15 (12), 9753. doi:10.3390/su15129753

Hanzaei, S. H., Gorji, S. A., and Ektesabi, M. (2020). A scheme-based review of MPPT techniques with respect to input variables including solar irradiance and PV arrays' temperature. *IEEE Access* 8, 182229–182239. doi:10.1109/access.2020.3028580

Hashim, H. F., Kareem, M. M., Al-Azzawi, W. K., and Ali, A. H. (2021). Improving the performance of photovoltaic module during partial shading using ANN. *Int. J. Power Electron. Drive Syst.* 12 (4), 2435. doi:10.11591/ijpeds.v12.i4.pp2435-2442

Ibrahim, S. A., Nasr, A., and Enany, M. A. (2021). Maximum power point tracking using ANFIS for a reconfigurable PV-based battery charger under non-uniform operating conditions. *IEEE Access* 9, 114457–114467. doi:10.1109/access.2021.3103039

Izam, N. S. M. N., Itam, Z., Sing, W. L., and Syamsir, A. (2022). Sustainable development perspectives of solar energy technologies with focus on solar Photovoltaic—a review. *Energies* 15 (8), 2790. doi:10.3390/en15082790

Jackson, M. M., Lewis, J. I., and Zhang, X. (2021). A green expansion: China's role in the global deployment and transfer of solar photovoltaic technology. *Energy Sustain. Dev.* 60, 90–101. doi:10.1016/j.esd.2020.12.006

Janandra Krishna Kishore, D., Mohamed, M. R., Sudhakar, K., and Peddakapu, K. (2022). Grey wolf optimization and differential evolution-based maximum power point tracking controller for photovoltaic systems under partial shading conditions. *Energy Sources, Part A Recovery, Util. Environ. Eff.* 44 (3), 6286–6302. doi:10.1080/15567036.2022.2096154

Kishore, D. J. K., Mohamed, M. R., Sudhakar, K., and Peddakapu, K. (2023a). A new meta-heuristic optimization-based MPPT control technique for green energy harvesting from photovoltaic systems under different atmospheric conditions. *Environ. Sci. Pollut. Res.* 30, 84167–84182. doi:10.1007/s11356-023-28248-8

Kishore, D. K., Mohamed, M., Sudhakar, K., and Peddakapu, K. (2023b). Swarm intelligence-based MPPT design for PV systems under diverse partial shading conditions. *Energy* 265, 126366. doi:10.1016/j.energy.2022.126366

Malik, M. Z., Baloch, M. H., Ali, B., Khahro, S. H., Soomro, A. M., Abbas, G., et al. (2021). Power supply to local communities through wind energy integration: an opportunity through China-Pakistan economic corridor (CPEC). *IEEE Access* 9, 66751–66768. doi:10.1109/ACCESS.2021.3076181

Mirsaeidi, S., Devkota, S., Wang, X., Tzelepis, D., Abbas, G., Alshahir, A., et al. (2023). A review on optimization objectives for power system operation improvement using FACTS devices. *Energies* 16 (1), 161–224. doi:10.3390/en16010161

Mohammed, K. K., Buyamin, S., Shams, I., and Mekhilef, S. (2021). Maximum power point tracking based on adaptive neuro-fuzzy inference systems for a photovoltaic system with fast varying load conditions. *Int. Trans. Electr. Energy Syst.* 31 (6), e12904. doi:10.1002/2050-7038.12904

Motahhir, S., El Hammoumi, A., and El Ghzizal, A. (2020). The most used MPPT algorithms: review and the suitable low-cost embedded board for each algorithm. *J. Clean. Prod.* 246, 118983. doi:10.1016/j.jclepro.2019.118983

Nassef, A. M., Houssein, E. H., Helmy, B. E. d., and Rezk, H. (2022). Modified honey badger algorithm based global MPPT for triple-junction solar photovoltaic system under partial shading condition and global optimization. *Energy* 254, 124363. doi:10.1016/j.energy.2022.124363

Osman, M. H., et al. (2022). Highly efficient MPP tracker based on adaptive neuro-fuzzy inference system for stand-alone photovoltaic generator system. *Int. J. Renew. Energy Res. (IJRER)* 12 (1), 208–217.

Pattnaik, M., Badoni, M., and Tatte, Y. (2021). Design and analysis of adaptive neuro-fuzzy inference system based MPPT technology. IEEE 18th India Council International Conference (INDICON), 19-21 Dec. 2021, USA, IEEE.

Qazi, A., Hussain, F., Rahim, N. A., Hardaker, G., Alghazzawi, D., Shaban, K., et al. (2019). Towards sustainable energy: a systematic review of renewable energy sources, technologies, and public opinions. *IEEE access* 7, 63837–63851. doi:10.1109/access.2019.2906402

Rafikiran, S., Hussaian Basha, C., Devadasu, G., Mary Tom, P., Fathima, F., and Prashanth, V. (2023). Design of high voltage gain converter for fuel cell based EV application with hybrid optimization MPPT controller. *Mater. Today Proc.* doi:10.1016/j.matpr.2023.03.770

Raza, M. A., Aman, M. M., Abro, A. G., Shahid, M., Ara, D., Waseer, T. A., et al. (2023a). A simulation model of climate policy analysis for sustainable environment in Pakistan. *Environ. Prog. Sustain. Energy* 42, e14144. doi:10.1002/ep.14144

Raza, M. A., Aman, M. M., Abro, A. G., Shahid, M., Ara, D., Waseer, T. A., et al. (2023d). The role of techno-economic factors for net zero carbon emissions in Pakistan. *AIMS Energy* 11 (2), 239–255. doi:10.3934/energy.2023013

Raza, M. A., Aman, M. M., Ghani Abro, A., Shahid, M., Ara, D., Waseer, T. A., et al. (2023c). Modelling and development of sustainable energy systems. *AIMS Energy* 11 (2), 256–270. doi:10.3934/energy.2023014

Raza, M. A., Aman, M. M., Rajpar, A. H., Bashir, M. B. A., and Jumani, T. A. (2022c). Towards achieving 100% renewable energy supply for sustainable climate change in Pakistan. *Sustainability* 14 (24), 16547. doi:10.3390/su142416547

Raza, M. A., Aman, M. M., Tunio, N. A., Soomro, S. A., Shahid, M., Ara, D., et al. (2023b). Energy transition through bioelectricity in Pakistan: implications for limiting global mean temperature below 1.5 C. *Environ. Prog. Sustain. Energy* 42 (4), e14189. doi:10.1002/ep.14189

Raza, M. A., Khatri, K. L., Hussain, A., Rehman, H., Rubab, F., and Khan, A. (2022e). Sector-wise optimal energy demand forecasting for a developing country using LEAP software. *Eng. Proc.* 20, 6. doi:10.3390/engproc2022020006

Raza, M. A., Khatri, K. L., and Hussain, A. (2022a). Transition from fossilized to defossilized energy system in Pakistan. *Renew. Energy* 190, 19–29. doi:10.1016/j.renene.2022.03.059

Raza, M. A., Khatri, K. L., Israr, A., Ul Haque, M. I., Ahmed, M., Rafique, K., et al. (2022). Energy demand and production forecasting in Pakistan. *Energy Strategy Rev.* 39, 100788. doi:10.1016/j.esr.2021.100788

Raza, M. A., Khatri, K. L., Memon, M. A., Rafique, K., Haque, M. I. U., and Mirjat, N. H. (2022d). Exploitation of Thar coal field for power generation in Pakistan: a way forward to sustainable energy future. *Energy Explor. Exploitation* 40 (4), 1173–1196. doi:10.1177/01445987221082190

Raza, M. A., Khatri, K. L., Ul Haque, M. I., Shahid, M., Rafique, K., and Waseer, T. A. (2022b). Holistic and scientific approach to the development of sustainable energy policy framework for energy security in Pakistan. *Energy Rep.* 8, 4282–4302. doi:10.1016/j.egyr.2022.03.044

Rehan, M., Amir Raza, M., Ghani Abro, A., M Aman, M., Mohammad Ibrahim Ismail, I., Sattar Nizami, A., et al. (2023). A sustainable use of biomass for electrical energy harvesting using distributed generation systems. *Energy* 278, 128036. doi:10.1016/j.energy.2023.128036

Rehan, M., Raza, M. A., Aman, M., Abro, A. G., Ismail, I. M. I., Munir, S., et al. (2023). Untapping the potential of bioenergy for achieving sustainable energy future in Pakistan. *Energy* 275, 127472. doi:10.1016/j.energy.2023.127472

Seguel, J. L., Seleme, S. I., Jr, and Morais, L. M. (2022). Comparative study of Buck-Boost, SEPIC, Cuk and Zeta DC-DC converters using different MPPT methods for photovoltaic applications. *Energies* 15 (21), 7936. doi:10.3390/en15217936

Singh, V. P., Arya, S. K., and Shankar, A. (2023). A novel fuzzy based solar irradiation prediction approach for selection of solar panels in hisar (Haryana). *Cybern. Syst.* 54 (6), 914–937. doi:10.1080/01969722.2022.2122007

Srinivasan, S., Tiwari, R., Krishnamoorthy, M., Lalitha, M., and Raj, K. (2021). Neural network based MPPT control with reconfigured quadratic boost converter for fuel cell application. *Int. J. Hydrogen Energy* 46 (9), 6709–6719. doi:10.1016/j.ijhydene.2020.11.121

Subha, S., Nagalakshmi, S., and Retracted, ARTICLE (2021). RETRACTED ARTICLE: design of ANFIS controller for intelligent energy management in smart grid applications. *J. Ambient Intell. Humaniz. Comput.* 12 (6), 6117–6127. doi:10.1007/s12652-020-02180-y

Sundararaj, V., Anoop, V., Dixit, P., Arjaria, A., Chourasia, U., Bhambri, P., et al. (2020). CCGPA-MPPT: cauchy preferential crossover-based global pollination algorithm for MPPT in photovoltaic system. *Prog. Photovoltaics Res. Appl.* 28 (11), 1128–1145. doi:10.1002/pip.3315

Villegas-Mier, C. G., Rodriguez-Resendiz, J., Álvarez-Alvarado, J. M., Rodriguez-Resendiz, H., Herrera-Navarro, A. M., and Rodríguez-Abreo, O. (2021). Artificial neural networks in MPPT algorithms for optimization of photovoltaic power systems: a review. *Micromachines* 12 (10), 1260. doi:10.3390/mi12101260

Wu, Z., Zhuang, Y., Zhou, S., Xu, S., Yu, P., Du, J., et al. (2020). Bi-level planning of multi-functional vehicle charging stations considering land use types. *Energies* 13 (5), 1283. doi:10.3390/en13051283

Zhang, T., Liu, Y., Rao, Y., Li, X., and Zhao, Q. (2020). Optimal design of building environment with hybrid genetic algorithm, artificial neural network, multivariate regression analysis and fuzzy logic controller. *Build. Environ.* 175, 106810. doi:10.1016/j.buildenv.2020.106810

Zhou, S., He, D., Gu, W., Wu, Z., Abbas, G., Hong, Q., et al. (2019). Design and evaluation of operational scheduling approaches for HCNG penetrated integrated energy system. *IEEE Access* 7, 87792–87807. doi:10.1109/access.2019.2925197

Zimmerman, R., Panda, A., and Bulović, V. (2020). Techno-economic assessment and deployment strategies for vertically-mounted photovoltaic panels. *Appl. Energy* 276, 115149. doi:10.1016/j.apenergy.2020.115149

Nomenclature

PV	Photovoltaic
MPPT	Maximum Power Point Tracking
ANN	Artificial Neural Networks
ANFIS	Adaptive Neural and Fuzzy Inference System
FLC	Fuzzy Logic Controller
RET	Renewable Energy Technology
ABC	Teaching-learning (TL) and artificial bee colony
GMPP	Global Maximum Power Point
MPPTs	Here are the full forms of the mentioned
PSO	Particle Swarm Optimization
IGWO	Improved Grey Wolf Optimizer
MFO	Moth Flame Optimization
SSA	Salp Swarm Algorithm
SD	Standard Deviation
MAE	Mean Absolute Error
Suc. Rate	Successful rate
GWO	Gray Wolf Optimization
DE	Differential Evolution
LMPP	Local Maxima Peak Power
PSC	Shading Conditions
OBEO	Opposition-Based Equilibrium Optimizer
P&O	Perturb and Observe