Design of a perturb and observe and neural network algorithms-based maximum power point tracking for a grid-connected photovoltaic system

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ABSTRACT

Integrating photovoltaic systems (PV) into the grid has garnered significant attention due to increasing interest in renewable energy sources. Maximizing the PV systems output power is crucial for improving energy efficiency and reducing operating costs. This paper presents a comparative analysis of two different techniques of maximum power point tracking (MPPT): perturb and observe (P&O) and artificial neural network (ANN) MPPT, focusing on their application in grid-connected PV systems. The paper evaluates their performance under various operating conditions, including changes in irradiance and temperature, that are discussed in three cases. The comparative analysis includes metrics such as voltage regulation and power loss. MATLAB Simulink is utilized to implement P&O and ANN MPPT methods, which include a PV cell connected to an MPPT-controlled boost converter. The simulation demonstrates the power loss of the PV model as well as the voltage regulation in the three cases for the two methods. The results obtained in simulation and implementations show that the ANN method outperforms the P&O in the three cases discussed in terms of power loss, voltage regulation, and efficiency. The results also show that the change in output power from PV is noticeable when compared to changes in radiation, while the change is slight when temperatures change.

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1. INTRODUCTION

The sources of renewable energy are increasingly favored for electricity generation due to growing environmental concerns and declining interest in conventional power sources like natural gas, oil, coal, and nuclear energy. Among these alternatives, solar photovoltaic (PV) technology stands out for its minimal environmental impact, economic feasibility, and ease of fabrication. The transition of energy of solar PV production from low-power to high-power grid systems has been seamless, addressing the rising demand and integrating multiple energy sources via transmission lines. This integration aims to regulate accumulation, ensure continuity, reduce demands of power bank, and replace conventional sources with renewable and green alternatives [1]. Connecting PV systems to the grid presents one of the most significant challenges facing the solar energy industry, as these systems sometimes encounter electrical connection problems with the grid. This inefficient connection results in the loss of part of the energy produced from the solar cells, reducing the converting efficiency of energy from solar into electrical energy. To overcome this issue, various technologies are employed to enhance the connection of photovoltaic systems to the grid. These technologies include using maximum power point tracking (MPPT) techniques to improve electrical conductivity and reduce energy loss, as well as developing intelligent control systems for ensuring the maximum utilization of generated energy, as demonstrated in this paper.

The evolution of PV systems began with small-scale installations, gaining significant interest in levels of distribution between stakeholders of power system around 2009. Connecting PV solar panels to transmission and sub-transmission levels has further improved the electrical system. PV solar panels operate in various configurations, including isolation or grid-connected modes, and are utilized in microgrid schemes like farms of solar and solar rooftop installations [2].

Global solar PV electricity production has witnessed substantial growth in recent years, driven by environmental concerns, the impact of global warming, reduced PV incentives of government, costs of module, and an overall emphasis on renewable energy. According to the International Energy Agency (IEA), the global solar PV production reached 1179 TWh in year 2021, marking a 22 percent increase from the last year. Solar electricity demonstrated the second highest absolute growth in generation between all technologies of renewable energy in 2021, following energy from wind. Given this significant growth, plants of solar PV have garnered great attention in the energy markets [3].

A typical solar PV system comprises PV panels, MPPT, power converters, and/or inverters, regardless of the load demand. The configuration of the PV system depends on its connection to the grid or isolation from the main grid. The generated current by the panels undergoes filtration and/or transformation before connecting to the grid [4].

Various MPPT schemes, such as perturb and observe (P&O), incremental conductance (INC), hill climbing, and incremental resistance (IR), have been proposed for maximum power extraction. While P&O is widely used due to its simplicity, its fixed step size may limit accurate and fast tracking under varying operating conditions. Recent studies have explored smart schemes of MPPT like artificial neural network (ANN) approaches, the particle-swarm-optimization (PSO), and long short-term memory (LSTM) for addressing these challenges [5].

Jena *et al.* [6] conducted research to evaluate new algorithms for MPPT in grid-connected solar PV systems. Their study covered various conditions like partial shading, dusty environments, and changes in concentrations of greenhouse gas. They explored MPPT using P&O and genetic algorithms and introduced a model of particle swarm optimization-long short-term memory (PSO-LSTM) to enhance MPPT accuracy. Their comparative analysis across different scenarios revealed that the PSO-LSTM model outperformed existing methods in terms of tracking speed and accuracy. In partial shading situations, the PSO-LSTM model achieved a tracking time of 39.63 for 50% shading, a standard deviation of 34.49, and a tracking efficiency of 83.27%, demonstrating an 11.23% improvement over benchmark models.

Chellakhi *et al.* [7] introduced and tested a novel approach integrating an enhanced P&O technique with a three-stage charging controller (TSCC) in a standalone photovoltaic system for a battery station. Their focus was on optimizing power extraction from the photovoltaic array while extending the battery's lifespan. The proposed P&O approach is based on an auto tuning of perturbation size of step, providing automatic of the ratio of the duty of the converter which type is DC-DC buck. The study found that the enhanced P&O approach with TSCC importantly enhanced charging operations, ensuring output power, voltage, and current stability. Comparative analysis showed that the IMP-P&O approach achieved higher efficiency (99.6%) compared to conventional P&O methods (98.37%), with reduced fluctuations in tracking the maximum power-point (MPP). Additionally, the enhanced approach demonstrated improved stability and resilience throughout testing, with noticeable reductions in oscillations.

The investigation by Bhukya and Shanmugasundaram [8] conducted a performance investigation on a new MPPT in a PV system. They analyzed characteristics of IV and PV of the PV system for different parameters of temperature and irradiation. They implemented and verified the P&O algorithm for MPPT operation under varying environmental conditions. The main contributors found that the characteristics of the solar PV system are affected by varying temperatures and irradiation. They also investigated the operation of the P&O algorithm for MPPT and compared it with theoretical approaches. Additionally, they validated the MPPT operation through simulation studies using PSCAD software and presented results to confirm the effectiveness of the algorithm in tracking the MPP.

Saberi *et al.* [9] proposed an enhanced P&O algorithm for PV systems. They developed a new algorithm that addresses the problems faced due to the conventional P&O algorithm, like oscillations in steady-state and the MPP deviation. Their algorithm utilizes a variable step-size for decreasing the time of convergence, selects the duty cycle based on the last three duty cycle average values, and reduces the probability of deviation when the irradiance changes. They also attached extra modules to the original P&O algorithm structure for changing the step-size, improving the convergence time, and reducing oscillations around the MPP. They found that their proposed algorithm achieved a whole efficiency of 98.54% in simulations and practical experiments using a boost-switching converter. They demonstrated that their algorithm significantly enhanced the performance of the traditional P&O algorithm by reducing oscillations, improving time of convergence, and minimizing MPP deviation.

Reddy [10] conducted a study comparing the performance of PSO and P&O techniques for MPPT in photovoltaic systems. The study aimed to evaluate the tracking efficiency, performance, and speed of these two MPPT algorithms. The authors found that the PSO-based MPPT algorithm showed improved performance compared to the technique of P&O. The PSO algorithm was able to optimize the values and monitor the MPP under various conditions, demonstrating high efficiency in monitoring, the structure is simple, simple in implementation, and rapid in reaching the required solution. The results of the simulation indicated that the PSO technique provided in less time a stable MPP without oscillations.

Connecting photovoltaic cells to the grid is accompanied by several challenges, including the fact that solar energy production variations affect the grid's voltage levels and frequency. Additionally, the photovoltaic system operates at a constant voltage or current, which may not be the ideal operating point for generating maximum power. This leads to suboptimal energy harvesting, as the system may not utilize the full potential of the solar panels under different environmental conditions. This can result in increased energy loss, decreased efficiency, as well as interruptions in power supply or damage to sensitive equipment. Therefore, control mechanisms are required to maintain stability and compliance.

This paper suggests an improvement to the system of the PV connected to the grid by adding MPPT. The MPPT controller constantly adjusts the point of operating of the PV system for ensuring it operates at MPP, where it generates the most power for the given conditions. This optimization maximizes the output energy of the PV system, reduces power losses, enhances voltage regulation, and improves the efficiency of the PV system. Moreover, irradiance levels of solar and temperature change throughout the day and across seasons. MPPT enables the PV system to adapt to these changing conditions swiftly, ensuring maximum energy harvest regardless of variations in environmental factors. The results of using the MPPT controller revealed system optimization, reduced energy loss, improved voltage regulation, and efficiency under different weather conditions. The key contributions of this research are illustrated as follows:

- Introduce two distinct MPPT algorithms to enhance the output power, adapting to varying irradiance and temperature conditions. These algorithms, namely P&O and ANN, undergo meticulous design, analysis, and evaluation using MATLAB/Simulink to demonstrate the robustness of ANN against P&O, facilitating a comparative assessment of PV power loss, voltage regulation, and efficiency.
- Evaluate and compare the system to demonstrate the overall performance of each algorithm, representing an enhancement in the design of PV systems connected to the grid.
- Conduct an evaluation in three cases with different degrees of temperature and irradiance. The first case involves varying irradiance levels (ranging from 400 to 1,000 W/m^2) with a fixed temperature of 25 °C, the second case considers different temperatures (ranging from 25 °C to 40 °C) at a constant irradiance of 1,000 W/m^2, and the third case explores diverse irradiance levels (ranging from 400 to 1,000 W/m^2) with temperature variations (ranging from 25 °C to 40 °C). The results obtained through this simulation are then scrutinized for their implications on the efficacy of each algorithm within the MATLAB/Simulink environment.

The structure of this paper is organized as follows: section 1 introduces the introduction and literature review. In section 2, we delve into the components of a photovoltaic system integrated with the grid, exploring various MPPT techniques utilized in PV systems, and the role of inverters. Additionally, this section introduces the methodology that integrates the photovoltaic system with the grid through MPPT. Moving on to section 3, we present the experimental results achieved through modeling and simulation using MATLAB Simulink software, providing analyses and discussions of the findings obtained. Finally, section 4 serves as the conclusion of the paper, offering a summary of the main findings and contributions of this study.

2. METHOD

2.1. Photovoltaic system

A photovoltaic system, often referred to as a solar panel system, is a means of generating electrical power by harnessing the energy from the sun. This technology comprises various integral components, including solar panels, an inverter, a mounting structure, and a monitoring system. Solar panels are the heart of the photovoltaic system, converting sunlight into direct current (DC) electricity. The inverter plays a pivotal role in transforming DC into alternating current (AC), that is the standard shape of electricity utilized in cities. The mounting structure is responsible for securely affixing the solar panels to rooftops or the ground, while the monitoring system keeps track of system performance and provides alerts to the system owner in case of any issues [11]. The advantages of implementing a photovoltaic system encompass:

- Utilization of a renewable energy source: solar energy represents a sustainable and eco-friendly energy source, contributing to a reduction in our dependence on non-renewable fossil fuels.
- Minimal maintenance requirements: solar panels demand very little upkeep and can operate efficiently for extended periods, potentially exceeding 30 years.
- Economic energy production: a photovoltaic system can yield significant savings on energy expenses by generating electricity that can be consumed within homes and businesses.
- Positive environmental effects: a photovoltaic system can mitigate the impact of greenhouse gases into the atmosphere, lower the buildup of solid waste, and protect valuable water resources [12].
- The specification table of the 415 SunPower PV module is shown in Table 1.

The characteristics of the current-voltage (I-V) and power-voltage (P-V) of the panel, measured under varying conditions of temperature and solar irradiance for 7 series modules; 88 parallel strings, are illustrated in Figures 1 and 2 respectively.

Table 1. Specifications of the 415 W module (SunPower SPR-415)

Parameter	Value
Peak power Pmax	415 W
Rated voltage Vmp	72.9 V
Rated current Imp	5.69 A
Open circuit voltage Voc	85.3 V
Short circuit current Isc	6.09 A
Temperature coefficient of voltage	-0.229 V/oc
Temperature coefficient of current	0.030706 A/oc

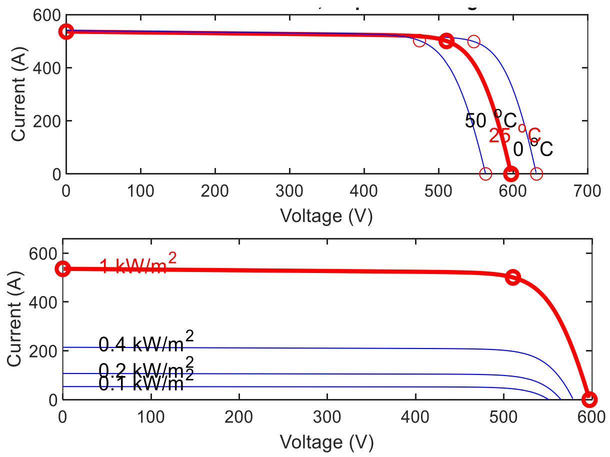


Figure 1. PV module I-V characteristics for different temperature and irradiance values

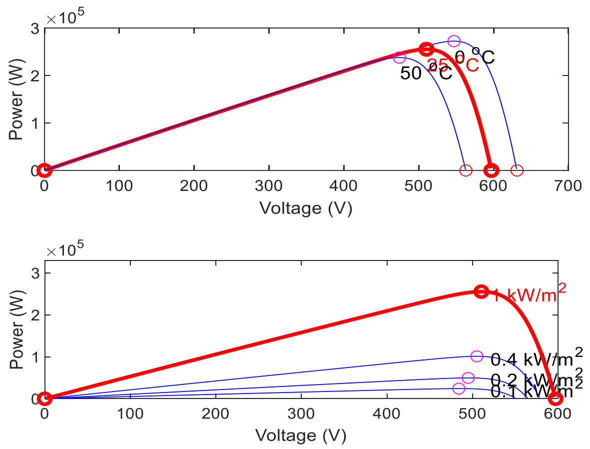


Figure 2. PV module P-V characteristics for different temperature and irradiance values

2.2. Maximum power point tracking

MPPT represents a technique employed in PV systems for optimizing the output power derived from solar panels. In PV systems, sunlight is converted into DC electricity, which can be used to power electrical devices or stored in batteries for future consumption. However, the power generated by a PV system is influenced by different factors such as temperature, shading, and the orientation of the panels relative to the sun. MPPT algorithms are utilized to continuously monitor and adapt the operating parameters of the PV system for ensuring that it operates at its MPP, where power production is maximized [13].

The MPP of a PV system corresponds to a specific combination of voltage and current at which the panels yield the highest output power. This relationship between voltage, current, and power in a PV system can be depicted through an I-V curve. Typically, this curve exhibits a characteristic shape, featuring a peak that signifies the MPP. By persistently monitoring and adjusting the operating conditions of the PV system, MPPT algorithms aim to maintain the system's operation as closely as possible to this MPP, thereby optimizing its power output. Also, it varies with irradiance and temperature [14].

In summary, MPPT plays an essential role in maximizing the power output of photovoltaic systems by dynamically adapting the operating parameters to track the MPP. Through the implementation of efficient MPPT algorithms, PV systems can operate at their highest efficiency, resulting in increased energy production and enhanced overall system performance. Lately, MPPT approaches have incorporated intelligent methods including PSO, genetic algorithms (GA), simulated annealing algorithms, fuzzy control, neural networks, and the firefly algorithm [15].

In this paper, P&O and ANNs are applied and introduced in this sub-section. The reason for applying ANNs is that they can model complex relationships and capture non-linearities in data, making them effective for tasks such as predictive modeling, fault detection, and system optimization in PV systems. PV systems exhibit complex and non-linear behavior due to factors such as weather conditions, irradiance, and equipment degradation. Also, ANNs can adapt to changing environmental conditions, grid dynamics, and system characteristics, leading to more robust and adaptive control strategies. ANNs are employed for accurate and rapid detection of the optimal power point amidst varying atmospheric conditions. Employing a radial basis function network as the fundamental neural-network reduces intricacy, enabling swifter tracking and diminishing the expenses associated with the development of advanced MPPT controllers [16].

2.2.1. Perturb and observation

The P&O technique stands as a commonly employed MPPT algorithm in PV systems. MPPT algorithms have a crucial role in PV systems by ensuring which solar panels function at their maximum power output, and optimizing energy conversion efficiency. The P&O algorithm is rooted in the continuous perturbation of the operating voltage of the PV system while simultaneously observing the resultant power output. By systematically adjusting the operating voltage and monitoring the power output, this algorithm effectively traces the MPP of the PV system. Fundamentally, the P&O algorithm hinges on comparing the power output at two consecutive voltage levels. If the power output increases, the system approaching the MPP, prompting the algorithm to persist in the same perturbation direction. Conversely, if the power output decreases, it signifies that the MPP has surpassed, leading the algorithm to reverse the perturbation direction [17].

The P&O algorithm is known for its simplicity of implementation and low computational resource demands. Nevertheless, it exhibits certain limitations that must considered. Notably, it is sensitive to abrupt fluctuations in irradiance or temperature, which can induce oscillations around the MPP, negatively affecting overall system performance. To mitigate this concern, various enhancements have proposed to elevate the P&O algorithm's performance. One approach involves introducing a variable step size for perturbation instead of relying on a fixed step size. This adjustment permits swifter tracking during stable conditions and minimizes oscillations during dynamic conditions [18].

In summary, the P&O algorithm is a widely recognized MPPT technique in PV systems. It operates by continually adjusting the operating voltage of the PV system while observing the resulting power output to trace the MPP. While the P&O algorithm is known for its simplicity, it may exhibit sensitivity to rapid environmental changes. Nonetheless, various modifications and advanced control techniques have proposed to enhance its performance and surmount these limitations [19]. Figure 3 provides further insight into the functionality of the traditional P&O algorithm [20].

2.2.2. Artificial neural-network

Artificial neural-networks (ANNs) play a crucial role in MPPT controllers by predicting voltage or output power at different times. The calculated value is then compared to real-time measurements for determining the optimal load cycle. In the initial layer of the network, independent variables like temperature (T) and solar irradiance (G) used as inputs, and additional factors such as panel voltage (V) and current (I) may also be considered [21].

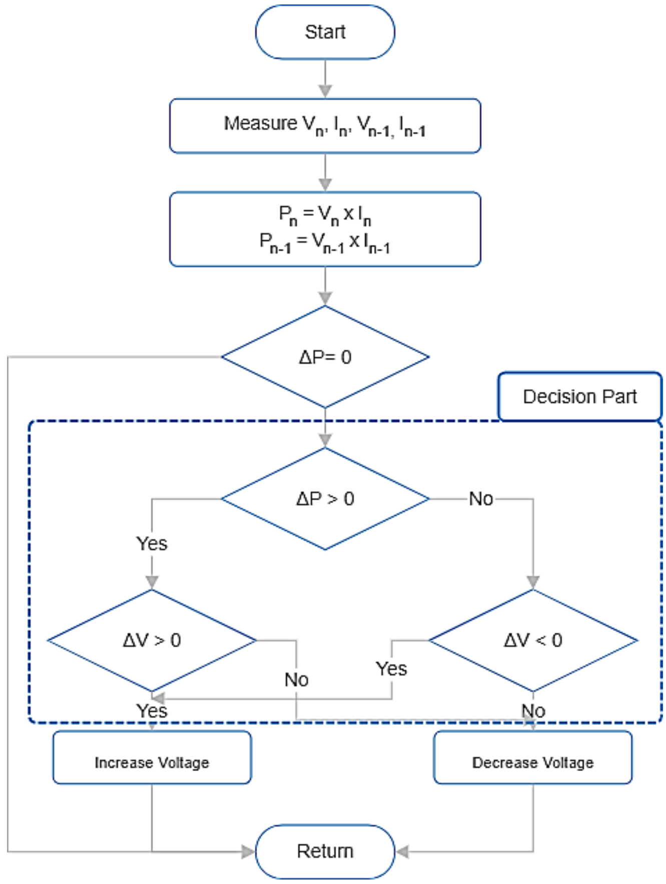


Figure 3. Flow chart of P&O algorithm

A trained ANN can analyze the providing data and offer forecasts and solutions for future problems. ANNs approach problem-solving differently from traditional predictive algorithms, resembling the adaptability of the human brain. They excel in scenarios with no clear algorithmic solutions or when dealing with imprecise data [22]. As a result, they find applications in diverse fields, including robotics, signal processing, pattern recognition, and financial analysis, enabling them to tackle problems that often challenge conventional computers. ANNs have garnered increased attention in the realm of MPPT control due to their capacity to discern intricate data patterns and adapt to non-linear relationships [23].

In the context of PV systems, ANNs can trained to forecast the MPP using historical data accumulated from the system. The ANN model can harness to oversee the MPPT algorithm, enabling it to adjust the solar panels' operating point to attain the peak output power. The integration of ANNs into MPPT carries several benefits, which encompass [24]:

- Enhanced precision: ANNs can decipher intricate data patterns and predict the maximum power point with remarkable accuracy, even when the Connection between input variables and output is non-linear.
- Adaptability to dynamic conditions: ANNs exhibit a remarkable ability to adapt to fluctuations in environmental factors like temperature and irradiance, allowing the MPPT algorithm to uphold optimal performance across time.
- Reduced computational intricacy: ANNs can streamline the MPPT algorithm by curtailing the number of calculations required for determining the maximum power point.

The ANN model consists of two inputs, three hidden layers, and one output layer. The inputs of this model are the solar irradiance (G) and temperature (T), while the current of the module chosen as output. The functionality of the ANN method becomes apparent when observing error charts. These visual aids depict the discrepancies between predicted and actual output voltage across various operational scenarios. The error charts provide the accuracy of the ANN algorithm's precision and effectiveness. They offer a tangible way to gauge how well the ANN method anticipates and manages voltage fluctuations, ultimately contributing to the assessment of its ability to sustain stable voltage levels [25]. The ANN method used is described by displaying error charts, as shown in Figure 4.

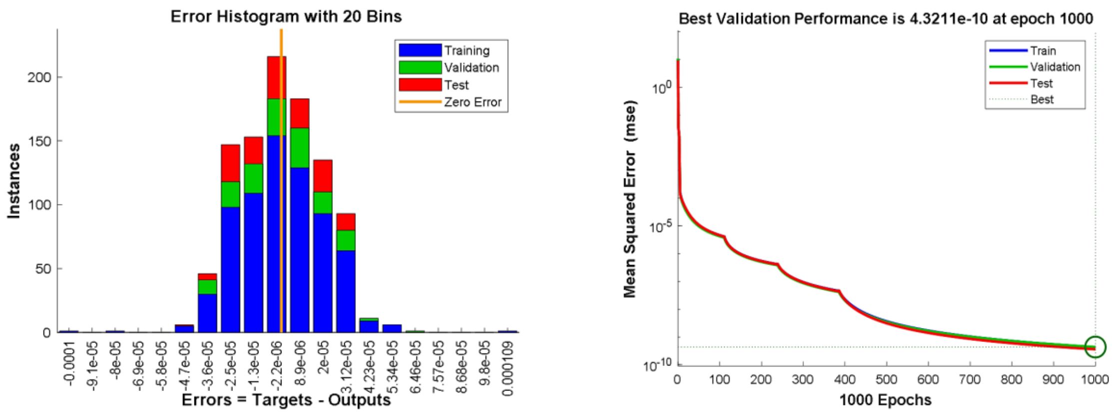


Figure 4. The ANN method error curves

2.3. Inverter

For ensuring the consistent provision of AC power to end-users from of renewable energy, the PV inverter must verify that the magnitude and frequency of the produced AC voltage adhere to acceptable thresholds [26]. The photovoltaic inverter (PVI) acts as the central component of a PV system and falls within the category of static converters. Its primary function involves converting the DC generated by the PV panels into AC compatible with the grid power and the electrical devices it supports, including batteries. PVIs are conventionally categorized into two types: standalone (SAPV) inverters, which operate independently from the grid, and grid-connected (GCPV) inverters, which are integrated with the public power grid. Nevertheless, modern systems have blurred this distinction, with many hybrid inverters now capable of functioning in both modes [27].

3. RESULTS AND DISCUSSION

3.1. Different irradiance and fixed temperature

3.1.1. Perturb and observation

The system is modeled and simulated using of MATLAB Simulink to validate the control method and assess system voltage regulation and power losses. Simulation outcomes for power losses and voltage regulation of the PV panel are obtained through the implementation of the P&O control technique under steady-state conditions at a temperature of 25 °C (T=25 °C) and varying irradiance levels within the range of 400 to 1,000 W/m². The results indicate that the P&O approach delivers power with big ripples. The results are clearly illustrated in Figure 5 which shows the irradiance change in Figure 5(a), the temperature is constant at 25 °C as in Figure 5(b), Figure 5(c) shows the output power over time, and Figure 5(d) display the ripple in the output power.

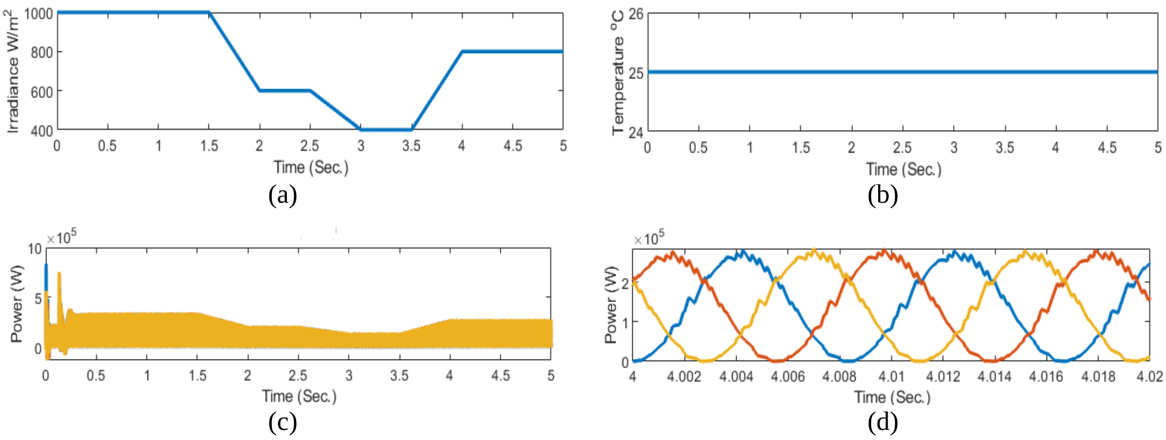
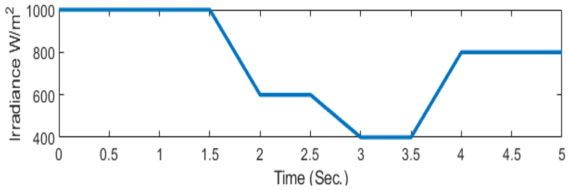


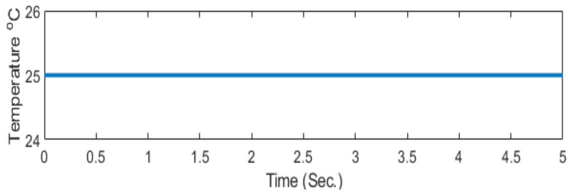
Figure 5. P&O MPPT at different irradiance and fixed temperature (a) the irradiance, (b) temperature, (c) output power over time, and (d) zoomed-in output power showing the ripple in the output power

3.1.2. Artificial neural-network

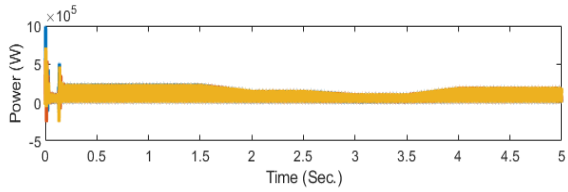
The outcomes of the simulation conducted on the PV panel within the MATLAB Simulink software environment, focusing on power loss and voltage regulation, were observed using the ANN method. a significant reduction in power loss and a remarkable improvement in voltage regulation when employing the ANN method. The results clearly illustrated in Figure 6 which shows the irradiance change in Figure 6(a), the temperature is constant at 25 °C as in Figure 6(b), Figure 6(c) shows the output power over time, and Figure 6(d) display the ripple in the output power.



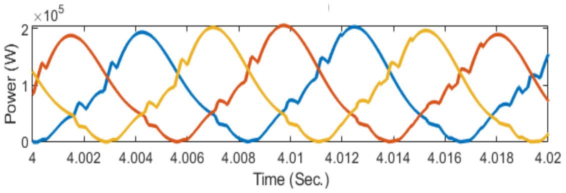
(a)



(b)



(c)



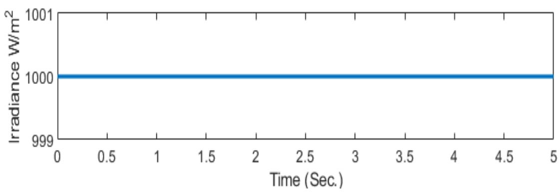
(d)

Figure 6. ANN MPPT at different irradiance and fixed temperatures (a) the irradiance, (b) temperature, (c) output power over time, and (d) zoomed-in output power showing the ripple in the output power

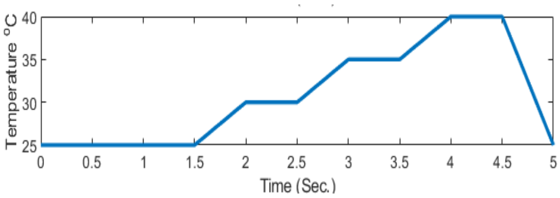
3.2. Different temperature and fixed irradiance

3.2.1. Perturb and observation

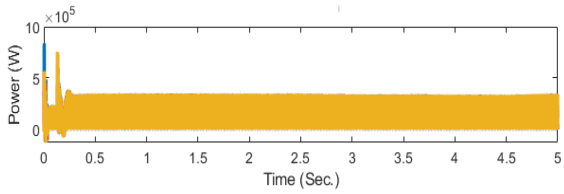
The simulated model illustrates a situation featuring fluctuating temperatures, spanning from 25 °C to 40 °C, alongside a consistent irradiance level set at 1,000 W/m². Employing the P&O algorithm within MATLAB Simulink produces outcomes that reveal a decline in power, as depicted in Figure 7. Figure 7(a) maintains a steady irradiance of 1,000 W/m², while Figure 7(b) illustrates the fluctuating temperature. Furthermore, Figure 7(c) displays the temporal evolution of output power, and Figure 7(d) exhibits the ripple effect in the output power.



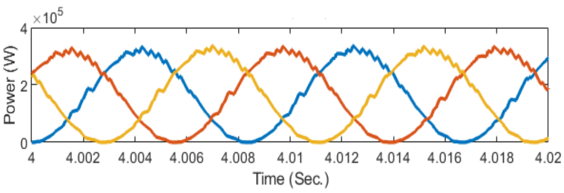
(a)



(b)



(c)



(d)

Figure 7. P&O MPPT at different temperatures and fixed irradiance (a) the irradiance, (b) temperature, (c) output power over time, and (d) zoomed-in output power showing the ripple in the output power

3.2.2. Artificial neural-network

The outcomes derived from the PV panel simulation utilizing the ANN approach within the MATLAB Simulink software unveil a significant decrease in power loss. These results highlight the effectiveness of the ANN method compared to the conventional P&O method, as demonstrated in Figure 8. Specifically, Figure 8(a) maintains a consistent irradiance of 1,000 W/m², while Figure 8(b) depicts the fluctuating temperature. Additionally, Figure 8(c) illustrates the temporal evolution of output power, while Figure 8(d) showcases the ripple effect in the output power.

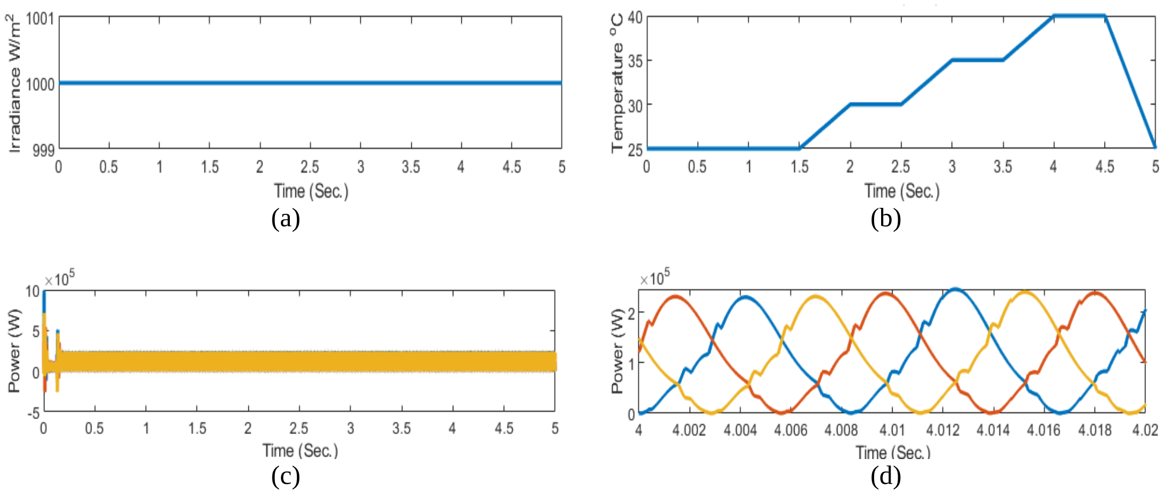


Figure 8. ANN MPPT at different temperatures and fixed irradiance (a) the irradiance, (b) temperature, (c) output power over time, and (d) zoomed-in output power showing the ripple in the output power

3.3. Different irradiance with different temperature

3.3.1. Perturb and observation

The simulations are carried out under diverse temperature scenarios, spanning from 25 °C to 40 °C, and across various irradiance levels ranging from 400 to 1,000 W/m². The results obtained underscore the efficacy of the P&O algorithm, as depicted in Figure 9. Specifically, Figure 9(a) illustrates the fluctuations in irradiance, while Figure 9(b) showcases the temperature variations. Furthermore, Figure 9(c) displays the temporal evolution of output power, with Figure 9(d) providing insight into the ripple effect in the output power.

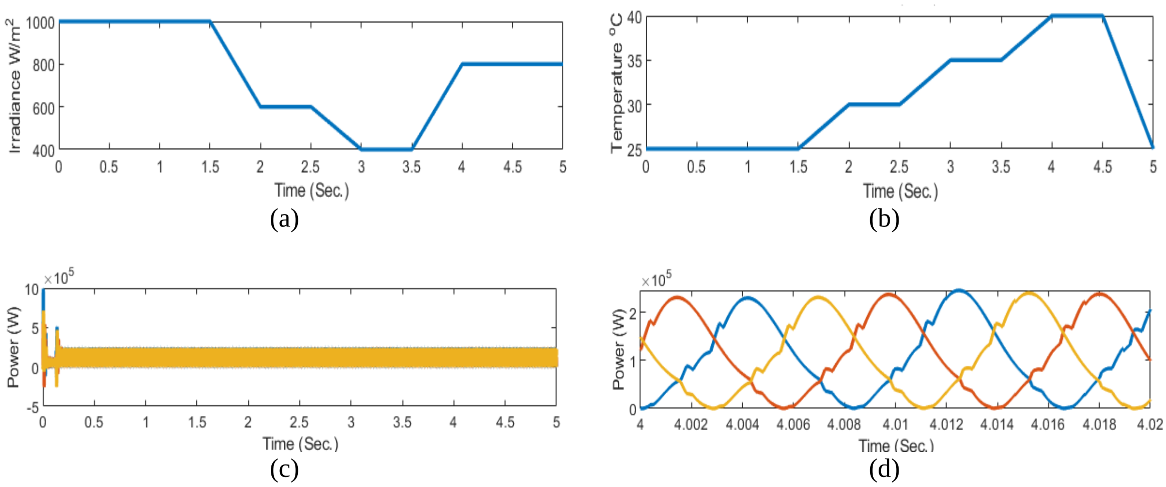


Figure 9. P&O MPPT at different irradiance and different temperatures (a) the irradiance, (b) temperature, (c) output power over time, and (d) zoomed-in output power showing the ripple in the output power

3.3.2. Artificial neural-network

The outcomes of the simulation conducted on the PV panel using the ANN method within the MATLAB Simulink software are observed under varying temperature conditions, ranging from 25 °C to 40 °C, and different irradiance levels spanning from 400 to 1,000 W/m². These results indicate that the ANN method delivered a remarkable reduction in power loss and a substantial improvement in voltage regulation. This underscores the superiority of the ANN method over the P&O method. The ANN algorithm results are shown in Figure 10, the change in irradiance is shown in Figure 10(a), the temperature varying shown in Figure 10(b), Figure 10(c) shows the output power over time, and Figure 10(d) display the ripple in the output power.

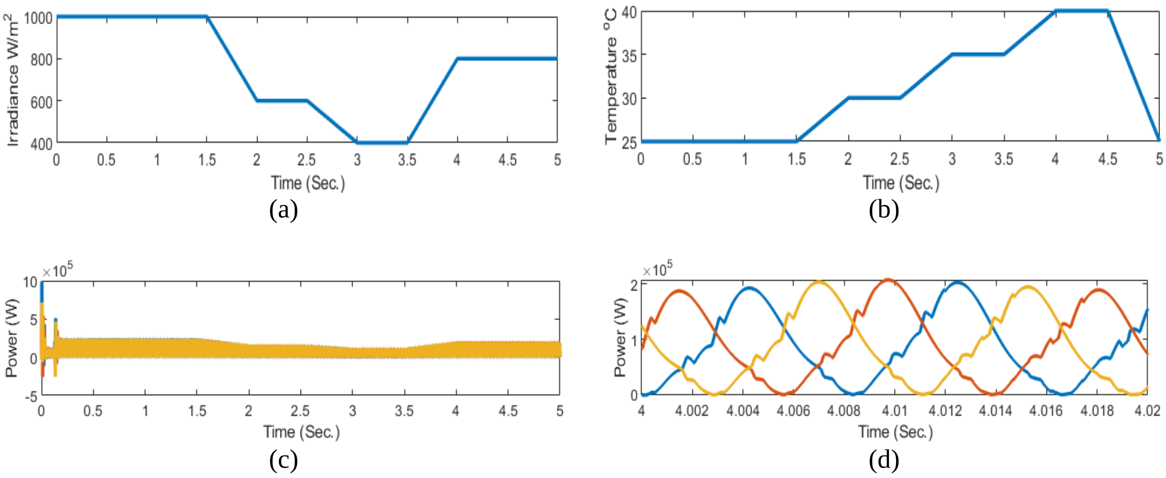


Figure 10. ANN MPPT at different irradiance and different temperatures (a) the irradiance, (b) temperature, (c) output power over time, and (d) zoomed-in output power showing the ripple in the output power

3.4. Simulation results for MPPT

In the end, the performance of the ANN and P&O algorithms are studied under the case of different irradiance and temperature and appears in the following results. The results show that the grid outputs power in both cases. In Figure 11, the results obtained for MPPT are presented. Figure 12 is a zoomed-in of Figure 11 highlighting the ripples in the output power of each mode. The results proved that the performance of the ANN algorithm, whose power ripple is less, is better than the P&O algorithm.

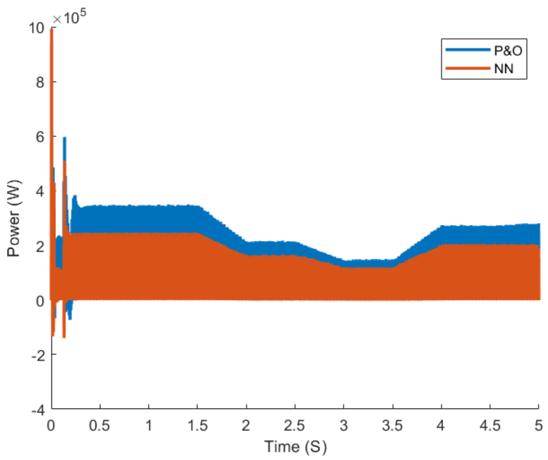


Figure 11. Comparison between P&O and ANN algorithms

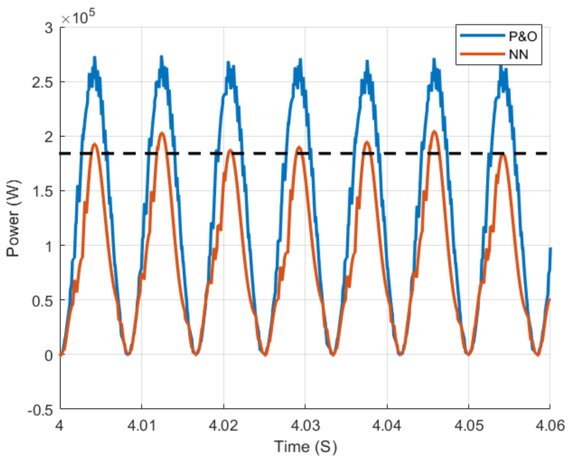


Figure 12. Zoomed-in Figure 11 showing the ripple in the grid power of P&O and ANN algorithms

3.5. Simulation results for voltage regulation

In conditions of the third case regarding the change in both irradiance and temperature, the voltage regulation outcomes between the ANN algorithm and the P&O algorithm were evaluated. The responses of the PV system's output voltage under both algorithms are depicted in Figure 13. Voltage regulation, which means stabilizing voltage levels despite fluctuations in demand and generation, was assessed based on these findings. The comparison revealed that the ANN algorithm exhibits superior voltage regulation performance compared to the P&O algorithm.

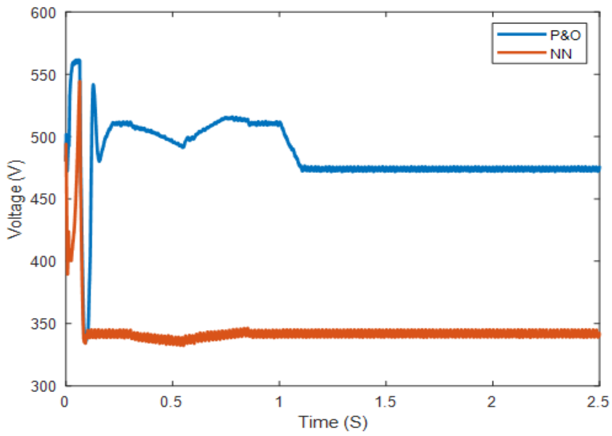


Figure 13. Output of PV system under different radiations and temperatures

Based on the PV curves of power, and their detailed examination presented in the preceding figures, it is evident that the ANN outperforms the P&O method in three distinct scenarios. Particularly noteworthy is the ANN's superior adaptability to abrupt fluctuations in temperature and irradiance, where the P&O method struggles, exhibiting significant oscillations that result in substantial power losses and voltage instability. In contrast, the ANN methodology effectively mitigates these issues and demonstrates remarkable precision in response to sudden changes in weather conditions. This superiority is further corroborated by the data summarized in Table 2, which underscores the ANN's superior efficiency across various conditions, characterized by reduced oscillations, minimized power losses, and overall enhanced performance. Also, a comparison with a study [7] made with fuzzy logic control (FLC), shows that the ANN gives better performance than FLC efficiency in the third case.

Table 2. Comparison performance of the ANN and P&O with other study

		P&O	ANN	FLC
Case 1	Power loss (%)	2.55	1.24	-
	Voltage regulation (%)			-
	Average efficiency (%)	97.39	98.75	-
Case 2	Power loss (%)	2.51	1.1	-
	Voltage regulation (%)			-
	Average efficiency (%)	97.45	98.82	-
	Power loss (%)	2.53	1.3	-
Case 3	Voltage regulation (%)			-
	Average efficiency (%)	97.37	98.71	98.4

3.6. Discussion

Adopting both P&O and ANNs MPPT algorithms yields significant improvements in the performance of PV systems connected to the grid. ANNs algorithm gives better results than the P&O algorithm in contributing to a marked reduction in power loss, enabling the system to operate closer to its peak efficiency by swiftly and accurately tracking the MPP under varying atmospheric conditions, ensuring stable and consistent voltage levels and minimizing fluctuations more than the P&O algorithm. Consequently, these advancements culminate in an overall increase in system efficiency, as the optimized operation facilitates maximum power output and minimizes energy wastage, thereby underscoring the efficacy of these algorithms in optimizing PV system performance and grid integration. Results demonstrated that the ANNs MPPT algorithm consistently outperformed traditional methods as the P&O algorithm, showcasing a substantial reduction in power loss of up to 1.3% in the third case which is better than P&O 2.53%. Also, the efficiency of ANN is better than P&O, and FLC in [7] by 98.71, 97.37, 98.4 respectively. This empirical evidence underscores the significant impact of ANN MPPT algorithms in optimizing PV system performance and grid integration, validating their efficacy in enhancing renewable energy utilization and sustainability.

This study specialized in comparing the two systems in terms of changes in irradiance and temperature by studying three cases and verifying the extent to which changes affect the power losses and voltage variation in each case. Thus, the study's strengths lie in its comprehensive analysis of P&O and ANN MPPT algorithms in addition to analysis of the impact of different irradiance and temperature, providing valuable insights into the optimization of PV system performance and their effectiveness in reducing power loss and enhancing voltage regulation. Previous studies have also investigated the efficacy of P&O and ANN MPPT algorithms in improving the performance of PV systems. As in [20] which researched the application of the P&O algorithm, in terms of complexity, accuracy, and cost. Also, the study [16], investigated an application of ANN in the system, in terms of power. All previous studies looked at improving the system without taking into consideration the change in weather factors such as temperature and radiation, and the results of that study showed the strength of their impact on the network. While the study provides valuable insights into the effectiveness of P&O and ANN MPPT algorithms in reducing power loss and enhancing voltage regulation, it is not without limitations. This study does not address potential challenges or limitations associated with the integration of these advanced MPPT techniques into existing PV systems, such as computational requirements or compatibility issues with legacy hardware and software components. Despite these limitations, the study's findings contribute valuable insights into the optimization of PV system performance using P&O and ANN MPPT algorithms, highlighting the need for further research to address these constraints and advance the field of renewable energy technology.

Thus, the study aimed to evaluate the efficacy of P&O and ANN MPPT algorithms in enhancing the performance of PV systems by reducing power loss, improving voltage regulation, and enhancing efficiency by conducting a comprehensive comparative analysis of changes in irradiance and temperature. The findings underscore the significance of employing advanced MPPT techniques, such as ANN in achieving substantial improvements in energy conversion efficiency and grid integration. This study is crucial as it validates the effectiveness of these algorithms and informs decision-making for stakeholders involved in renewable energy deployment, contributing to the advancement of sustainable energy technologies and the transition towards a greener and more resilient energy infrastructure.

4. CONCLUSION

The study conducts a comprehensive analysis of various MPPT techniques and performs a comparative assessment of P&O and ANN methods for tracking the MPP of solar panels. The Simulink models for both MPPT techniques consist of a solar panel, an algorithm block, and a grid interface. The research adopts three distinct scenarios. Preliminary results showed that the output power in the case of the ANN technique is better than in the case of the P&O technique because of the lack of ripples in the three scenarios based on the zoomed-in output power results.

The collected data indicates that the irradiance and temperature factors significantly influence PV output power, but the impact of irradiance tends to be more immediate, noticeable, and visible in the short term. Temperature also impactful might have a more gradual effect, especially as it accumulates over time or during specific environmental conditions. Also, about two MPPT techniques used, the ANN algorithm outperformed the P&O algorithm regarding power loss, voltage regulation, and efficiency. The ripple in power in the ANN technique is less than in the P&O technique. Furthermore, the voltage output graphs of the solar panels demonstrate that the ANN method exhibited superior performance due to its high voltage regulation compared to the P&O algorithm. Thus, the ANN technique provides a reliable and efficient performance of maximum power tracking under rapid changes in temperature and irradiance conditions.

Through our research, we have uncovered the significant benefits of MPPT. Firstly, these advanced MPPT techniques can integrated into various PV system designs to enhance performance and optimize energy production. Additionally, further research could explore the development of hybrid MPPT algorithms that combine the strengths of P&O and ANN approaches to achieve even the best efficiency gains and reliability. Moreover, applying these algorithms could extend beyond PV systems to other renewable energy technologies, such as wind and hydroelectric power generation, offering opportunities to improve overall energy sustainability and grid stability.

The findings of this study hold significant implications for both the research field and the community at large. These findings pave the way for the adoption of advanced MPPT techniques in PV system design and implementation, facilitating the transition towards a more sustainable and resilient energy infrastructure. Moreover, by optimizing the performance of PV systems, these algorithms can enhance energy affordability, reliability, and accessibility for communities worldwide, fostering greater energy independence and mitigating environmental impact. As such, these findings can drive innovation, inform policy decisions, and ultimately accelerate the global transition towards a cleaner and more sustainable energy future.

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