Available online at
http://uppp.uitm.edu.my/online-issues.html

e-ISSN: 2689-4934

ESTEEM Academic Journal Vol 20, September 2024, 135-146

ESTEEM Academic Journal (EAJ)

Performance evaluation of solar photovoltaic system based on perturb and observe (P&O) maximum power point tracking (MPPT) algorithm

Nurfarah Ayuni Abdul Khani[1], Muhammad Iqbal Zakaria[1*], Mohd Abdul Talib Mat Yusoh[1], Muhammad Nizam Kamarudin[2], Abdul Rahman A.A Emhemed[3]

[1]*School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA Shah Alam, Malaysia*
[2]*Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia*
[3]*College of Technical Engineering, Bright Star University, El-Brega, Libya*

ARTICLE INFO

Article history:
Received 31 May 2024
Revised 20 August 2024
Accepted 26 August 2024
Online first
Published 30 September 2024

Keywords:
Boost Converter
Maximum Power Point Tracking (MPPT)
Perturb and Observe (P&O)
Photovoltaic (PV) System

DOI:
10.24191/esteem.v20iSeptember.1593.g1826

ABSTRACT

The Photovoltaic system (PV) is gaining popularity as a future energy source due to its vast, secure, essentially limitless, and widely accessible nature. However, a prevalent challenge in PV systems is the impact of solar cell radiation intensity and temperature on the output power induced in the photovoltaic module. As a result, monitoring the input source's maximum power point becomes essential for maximizing the effectiveness of the renewable energy system. In order to harvest the most power from the photovoltaic system and channel it to the load through a boost converter, which raises the voltage to the necessary level, most Power Point Tracking, or MPPT, is essential. This study uses the Perturb and Observe (P&O) method to track the photovoltaic module's Maximum Power Point (MPP) and maximize the system's overall power production to overcome this obstacle. By varying the array terminal voltage or current, the P&O approach perturbs the system and then compares the PV output power to the preceding perturbation cycle. Therefore, the main goal of this study is to simulate and assess the effectiveness of the P&O MPPT algorithm in MATLAB/Simulink when it comes to maximizing power extraction from a photovoltaic system. The simulation findings show that the suggested P&O approach is a reliable means of tracking MPP from PV panels, even when there are fluctuations in solar irradiation.

[1*] Corresponding author. *E-mail address:* iqbal.z@uitm.edu.my
https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

1. INTRODUCTION

Growing concerns about environmental issues and global warming have sparked significant motivation to shift toward renewable energy sources. In response to the escalating global demand for energy, extensive research and development efforts have been directed towards alternative, environmentally friendly energy sources [1]. Among these alternatives, electrical energy harnessed from photovoltaic (PV) cells emerges as an increasingly viable natural energy option. Its appeal lies in being free, abundant, clean, and universally available across the Earth. Additionally, PV energy plays a pivotal role as a primary contributor to various energy production processes on Earth [2]. To address these environmental concerns and support the ongoing shift to renewable energy, this research focuses on the characteristics of PV modules. Specifically, it investigates the intricacies of the P-V curve and the concept of the Maximum Power Point (MPP), emphasizing the importance of the Maximum Power Point Tracking (MPPT). These aspects are fundamental in enhancing the understanding of PV systems and optimizing efficiency for sustainable energy solutions.

Exploring the critical characteristics of PV modules, which are essential for optimizing the efficiency of electrical energy production, factors such as irradiation and temperature significantly influence the performance of PV systems. This highlights the importance of the MPPT algorithm, which aims to fine-tune the operational parameters of the PV system for maximum power output [3]. The MPPT algorithm acts as the “brain” of the solar power system, continuously monitoring and adjusting the operating point of the PV modules. Its primary objective is to ensure that the system consistently operates at or near the MPP, at which the PV modules produce the highest possible power output under given environmental conditions. To achieve this optimization, various MPPT techniques are commonly used and recommended in scientific literature, with notable examples being the Fuzzy Logic Controller (FLC) [4], Incremental Conductance (INC) [5], and Perturb and Observe (P&O) [6-7] methods.

The utilization of an FLC for tracking the MPP has gained prominence due to its design simplicity, robustness, and ability to operate with imprecise inputs. FLC excels in scenarios where an accurate mathematical model is not readily available andadeptly handles nonlinearity [4]. The structure of the FLC consists of three fundamental stages: fuzzification, aggregation, and defuzzification [8]. In the fuzzification stage, numerical input variables are transformed into membership functions. The system’s output establishes linguistic relationships with the input system, which are articulated through rules. Each rule generates a fuzzy set, and the inclusion of multiple rules is often employed to enhance conversion efficiency. Furthermore, aggregation involves combining the output fuzzy sets from individual rules into a unified output fuzzy set. Finally, the fuzzy set is converted into precise output. This multi-stage approach of the FLC contributes to its effectiveness in maximizing power extraction under varying conditions.

Additionally, the INC algorithm is a frequently employed in PV systems for tracking the MPP. This algorithm operates by comparing the instantaneous and incremental conductance of the PV array. However, the INC algorithm encounters a challenge similar to that faced by the P&O method, where a fixed step size is conventionally used to balance accuracy and response speed in MPPT [5]. Consequently, a trade-off is necessary between steady-state performance and tracking speed. Implementing variable step size MPPT strategies offers a solution to this problem. To dynamically adjust the step size of MPPT, the power derivative to voltage (dP/dV) is used [9]. When the operating point deviates significantly from the MPP, the step size is increased, gradually decreasing as the operating point approaches the MPP. This adaptive step size adjustment facilitates rapid tracking speed and stable output, though it requires the inclusion of a scaling factor to ensure algorithm convergence.

On the other hand, the P&O algorithm is another viable method for tracking the MPP. Known for its simplicity and ease of implementation, the P&O algorithm perturbs the array terminal voltage or current, comparing the PV output power with the previous perturbation cycle [10-12]. The control system modifies the PV array's operating point in response to an increase in power caused by a change in operating voltage;

https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

if not, the operating point moves oppositely. This iterative process continues in subsequent perturbation cycles. The advantages of the P&O method include its simplicity, straightforward control scheme, cost-effectiveness compared to other techniques, and ability to generate high output power [13-15]. Therefore, this study aims to assess how well a PV system's P&O MPPT algorithm performs in terms of optimal power extraction. There are four sections in the remaining portion of the paper. Section 2 details the PV system description, including the PV panel model and power converter. Section 3 focuses on the P&O-based MPPT, and Section 4 discusses the simulation results and findings obtained from MATLAB/Simulink. Finally, Section 5 presents the conclusion.

2. PHOTOVOLTAIC SYSTEM DESCRIPTION

Fig. 1 illustrates the PV system featuring the MPPT controller. The design of the photovoltaic system is divided into two components: the modelling of the photovoltaic array and the modelling of the MPPT boost DC-DC converter. The load impedance, as perceived by the source, is adjusted and matched to the peak power point of the source, facilitating the transmission of maximum power. The parameters denoted by T, G, V_{pv} and I_{pv} Fig. 1 corresponds to temperature, solar irradiance, PV voltage, and PV current. In Fig. 1, temperature, solar irradiance, PV voltage, and PV current correspond.

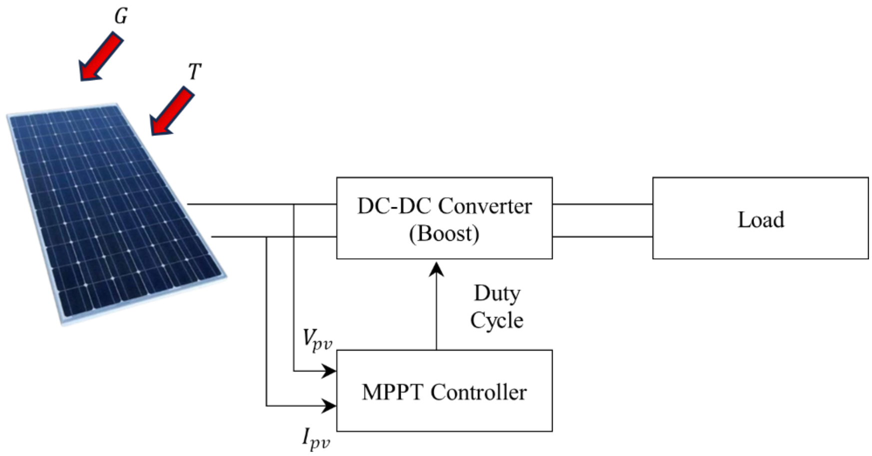

Fig. 1. Photovoltaic system integrated with MPPT controller

2.1 PV panel model

Photovoltaic cells are used in solar photovoltaics to convert sunlight into electrical power. These cells, fundamental components of a photovoltaic system, directly generate direct current (DC) electricity when exposed to sunlight. Fig. 2. shows a photovoltaic array model consisting of a current source, a diode, and resistance. Like a diode, photovoltaic cells have a p-n junction formed within a semiconductor material [16]. They utilize photons from sunlight to generate electricity by absorbing solar radiation and converting the energy of the photons into electrical power. When a photovoltaic cell is attached to a load and exposed to sunlight, it produces a direct current until sunlight is no longer available. T. The connections between the cells are either parallel or series to achieve the desired voltage or current output. They are connecting cells in series results in a higher output voltage, whereas connecting them in parallel increases the output current.

https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

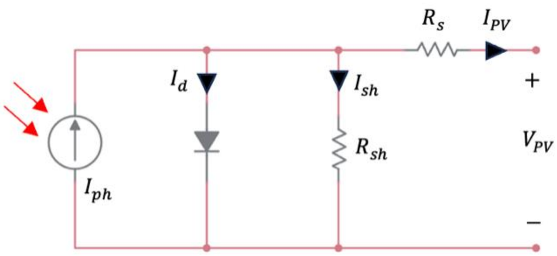

Fig. 2. PV array modelling circuit

Accurately characterizing a PV system requires a reliable and well-established model that accounts for the effects of temperature, solar irradiance, and heat dissipation. Fig. 2. illustrates a detailed schematic of a PV circuit. A typical PV array comprises multiple modules to achieve the desired output voltage and current, as described in the following Eq. (1) and Eq. (2) [17].

$$V_{PV} = \frac{nKT}{q} \ln\left(\frac{I_{ph}}{I_{PV}} + 1\right) \tag{1}$$

$$I_{PV} = I_{ph} - I_{PV0}\left[\exp\left(\frac{q(V_{PV} + I_{PV}R_s)}{nKT} - 1\right)\right] - \frac{V_{PV} + R_s I_{PV}}{R_{sh}} \tag{2}$$

In Fig. 2, the resistance arranged in series is identified as R_s , and it is measured in ohms. Similarly, the shunt (parallel) resistance is designated as R_{sh}, also measured in ohms. Additionally, the photocurrent of the PV cell is represented by the variable. I_{ph}. It is essential to note that the temperature of the cell, denoted by T, is measured in Kelvin.

2.2 Power converter

A DC-DC converter is an electronic system that converts a DC source voltage from one range to another [18]. Researchers frequently utilize it to enhance or raise the output voltage of renewable energy sources, such as wind, solar, and fuel cell systems. The DC-DC boost converter raises the input DC voltage by connecting two semiconductor devices (diodes or transistors) across the DC load, an output capacitor, and an inductor. Because the output voltage of this kind of converter is higher than the source voltage, it is known as a step-up converter. Fig. 3 illustrates the typical configuration of a DC-DC boost converter, which is widely used in photovoltaic system applications. In modelling the boost converter, all components are assumed to be ideal, and the converter operates in continuous conduction mode.

Typically, when the power switch in a boost converter is activated, the inductor stores energy in the form of an electromagnetic field and releases this energy when the power switch is deactivated [19]. The time constant (RC time constraint) depends on the size of the capacitor. The resulting equation (Eq. (3)) can be derived upon inspecting the circuit depicted in Fig. 3.

$$(V_{in} \times D \times t) + (V_{in} - V_{out}) \times (1 - D) \times t = 0 \tag{3}$$

https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

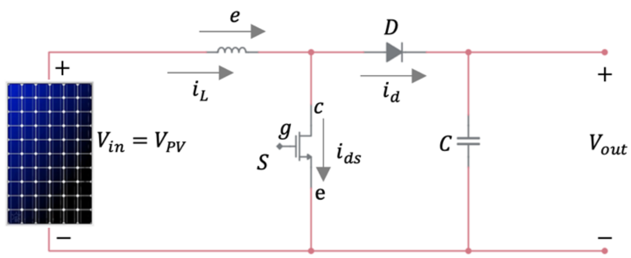

Fig. 3. DC-DC boost converter circuit.

Here, t represents the opening and closing time of the switch, D is the duty cycle, with a value ranging from 0 to 1, $D.t$ is the ON time of the switch, and $(1-D)t$ is the switch's closing time. Therefore, the output voltage can be expressed as in Eq. (4):

$$V_{out} = \left(\frac{1}{1-D}\right) \times V_{in} \quad (4)$$

The correlation between output voltage and input voltage can be expressed as $V_{out} = V_I(1-D)$. Due to the conservation of power before and after conversion, $I_o = I_I(1-D)$. Thus, the equivalent resistance is (Eq. (5):

$$R_{eq} = \frac{V_{out}}{I_I} = \frac{V_I(1-D)}{I_o/(1-D)} = R_I(1-D)^2 \quad (5)$$

The formula above (Eq. 5) shows that adjusting the switching duty cycle (D) in the boost circuit affects the input impedance. The objective is to match the output impedance of the solar array with the equivalent input impedance of the boost circuit by adjusting D. The solar cell will produce its maximum output power because of this alignment.

3. PERTURB AND OBSERVE (P&O) BASED MAXIMUM POWER POINT TRACKING (MPPT)

P&O algorithms are widely employed for MPPT due to their straightforward structure and minimal parameter measurement requirements. The operational principle of the P&O algorithm involves periodic perturbation, either increasing or decreasing the voltage array, followed by a comparison of photovoltaic output power with that of the previous perturbation cycle [20-21]. The perturbation direction is maintained when power increases; otherwise, it is reversed. This implies that the array's terminal voltage undergoes perturbation in each MPPT cycle. Consequently, the P&O algorithm exhibits fluctuations, resulting in a decline in photovoltaic power, particularly when atmospheric conditions are subject to constant or gradual changes. In this work, the challenge is addressed by enhancing the P&O algorithm's logic, which involves comparing parameters from two previous cycles to assess the algorithm's status, allowing it to bypass the perturbation stage when the desired condition is achieved.

Implementing P&O type MPPT with increased current refresh rates necessitates two key considerations. First, the P&O algorithm must operate at significantly high sampling rates to ensure that

https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

the voltage and current sample values accurately reflect the trend of output power, whether decreasing or increasing, relative to the reference signal for the MPPT power converter. Second, while maintaining a low frequency, the response time of the MPPT power converter should be fast. This can be achieved by comparing instantaneous values rather than averages of PV voltage and peak current control. This approach enables a one-cycle response for minor variations in the reference current, thereby improving system performance.

Fig. 4 illustrates the flowchart detailing the proposed P&O MPPT algorithm. The P&O algorithm operates through iterative trial-and-error processes to identify the maximum PowerPoint precisely. It examines power variations and adjusts the operating voltage of the photovoltaic panel, thereby modifying the effective input resistance of the boost converter by adjusting the duty cycle of the converter's switching device. The flowchart is described as follows: Initially if both. V_{pv} and P_{pv} exhibit positive or negative variations, the duty cycle (D) is increased by a step size of ΔD. Conversely, if the variations in V_{pv} and P_{pv} have opposite signs, the duty cycle (D) is decreased by a step size of ΔD. This cyclic process is repeated and monitored until the maximum power point is achieved. The algorithm follows the same procedure in subsequent perturbation cycles. Notably, a large ΔD ensures rapid dynamic performance but introduces non-negligible oscillations in a steady state. On the other hand, a small ΔD results in minimal fluctuation at the steady state, though it leads to a slower dynamic response. Striking a balance between fast dynamic response and minimizing steady-state oscillations is a crucial design consideration for this algorithm. This balance is essential to maintaining the generated output power at the MPP.

4. SIMULATION RESULTS AND DISCUSSION

The system is modelled and simulated using MATLAB/Simulink software to validate the control strategy and assess system performance, as shown in Fig. 5. Within MATLAB, the Simulink model is utilized, specifically the Simscape/Electrical/Specialized Power Systems/Renewables/Solar toolbox. The model incorporates a photovoltaic representation based on the 1Soltech 1STH-215-P model, a boost converter, and the proposed P&O MPPT algorithm. Solar irradiance and ambient temperature are inputs to the PV module. The PV module then produces PV voltage and PV current, which serve as controlled sources for the input of the boost converter.

This study investigates the impact of various climatic conditions on the operation of a PV system using the proposed P&O algorithm scheme through a comprehensive case study. The focus is on quantifying the influence of sudden changes in solar irradiance while maintaining a constant temperature on the PV system's performance. To evaluate the efficiency of the proposed P&O method, irradiance is varied in a 'hill-shaped' profile with the temperature fixed at 25 ºC. Fig. 6 illustrates the irradiance profile (W/m²) against time (seconds), depicting a hill-shaped curve. The profile begins at zero (0 W/m²) and rapidly increases, reaching a peak of approximately 1000 W/m² between 1.7 and 2.5 seconds. After reaching its peak, the profile symmetrically declines at a similar rate, eventually returning to zero at around 4 seconds. This hill-shaped profile mimics the irradiance variations that may occur over a short period, possibly simulating certain weather conditions such as clouds passing over the sun, causing quick drops and rises in the amount of solar radiation received by PV panels. This irradiance profile serves as an input in PV system simulations to test the effectiveness of the proposed P&O method. Using this variable profile makes it possible to assess how well the method optimizes energy generation from the PV system, even under dynamically changing irradiance conditions.

The simulated results of the studied system, illustrating the controller's performance, are shown in Fig. 7 through Fig. 10. These results reveal the impressive dynamic performance of the developed controller based on the proposed P&O algorithm, which showcases reduced oscillations in power output. Notably, the voltage remains relatively stable, hovering around 138 V with only minor fluctuations throughout the simulation period, as seen in Fig. 7. The overall voltage stability indicates that the proposed MPPT

https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

algorithm effectively maintains the operating voltage close to the desired setpoint. The current exhibits more noticeable fluctuations, ranging from approximately 4.5 A to 6.5 A, throughout the simulation, as depicted in Fig. 8. These fluctuations suggest a potential correlation between voltage and current variations, which is expected in a photovoltaic system. In Fig. 9, the power output follows a similar trend to the current, fluctuating between roughly 585 W and 950 W during the simulation. Despite these fluctuations, the power output remains within a reasonable range, demonstrating the effectiveness of the proposed P&O algorithm in tracking the MPP and maintaining power output under changing operating conditions. Further analysis of the system's efficiency under various output power levels demonstrates how well the MPPT algorithm converts solar energy into electrical energy. Fig. 10 shows that the proposed P&O algorithm achieves high efficiency, reaching 98% during peak irradiance (approximately 0.75 s to 3.4 s). This evaluation compares the solar panel's input power to its output power, and the results are satisfactory, highlighting the maximized energy extraction from solar panels, regardless of weather conditions.

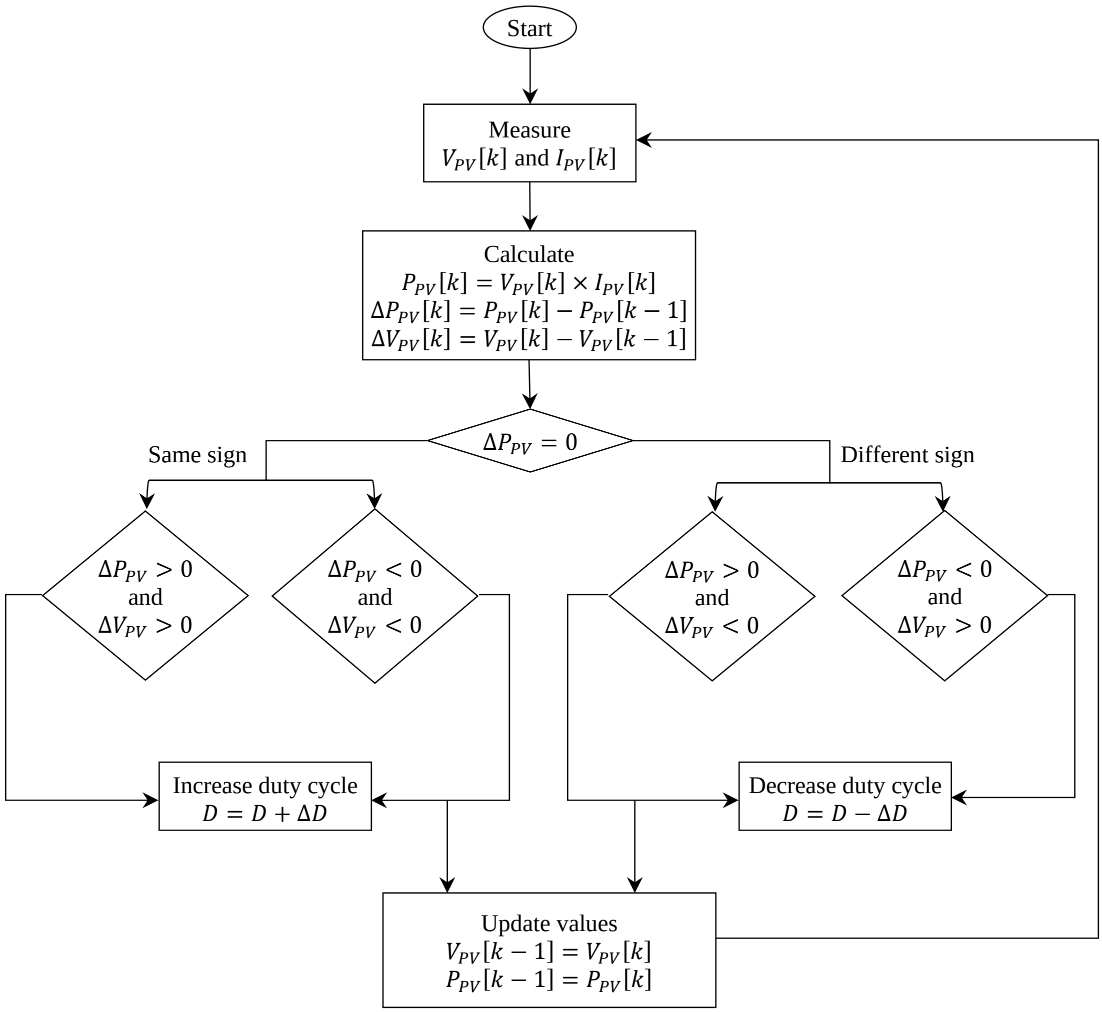

Fig. 4. Flowchart of the P&O MPPT algorithm

https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

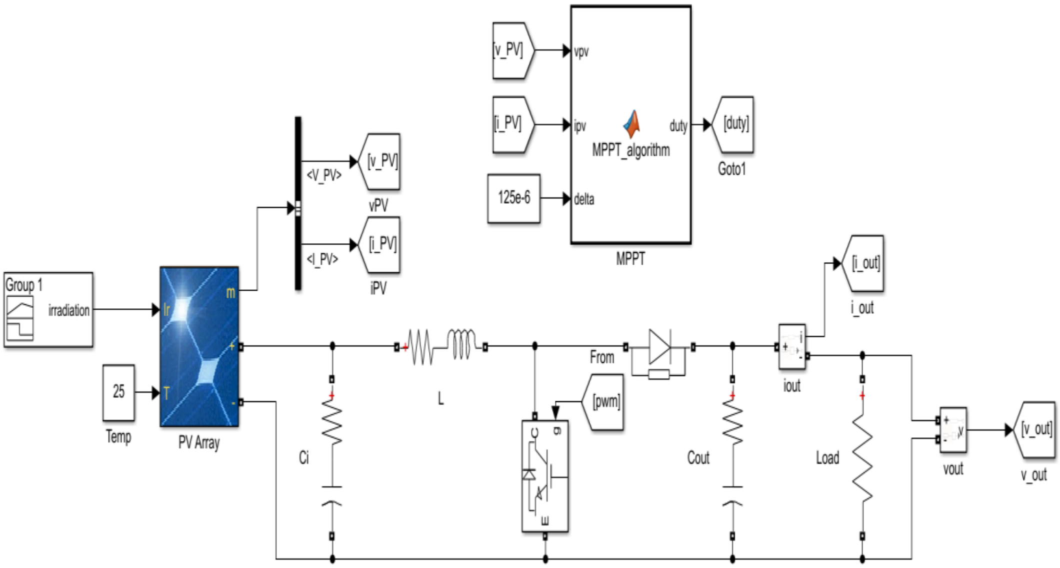

Fig. 5. Simulation circuit of PV module incorporating the proposed P&O MPPT algorithm

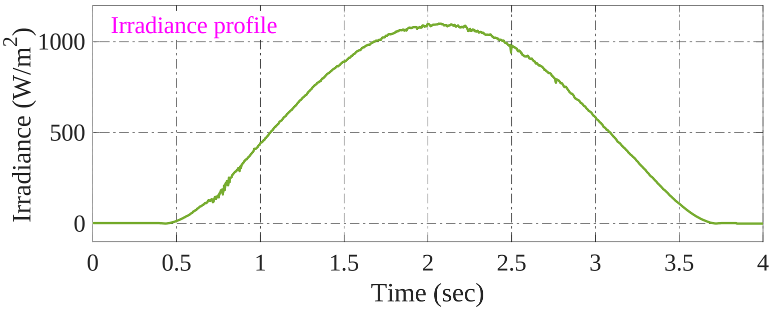

Fig. 6. Hill-shaped irradiance profile utilized as the input for the PV system simulation.

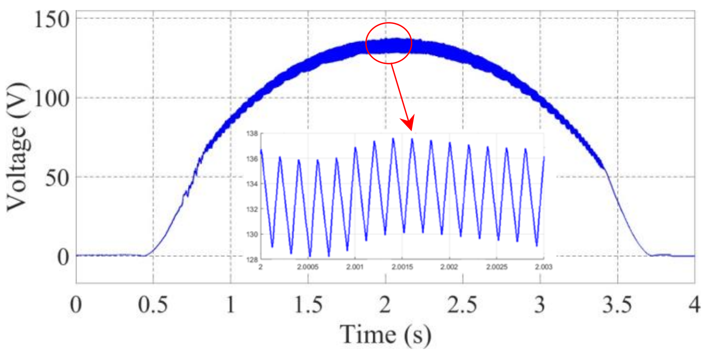

Fig. 7. Simulated PV output voltage waveform, showing variations due to changes in irradiance under constant temperature conditions

https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

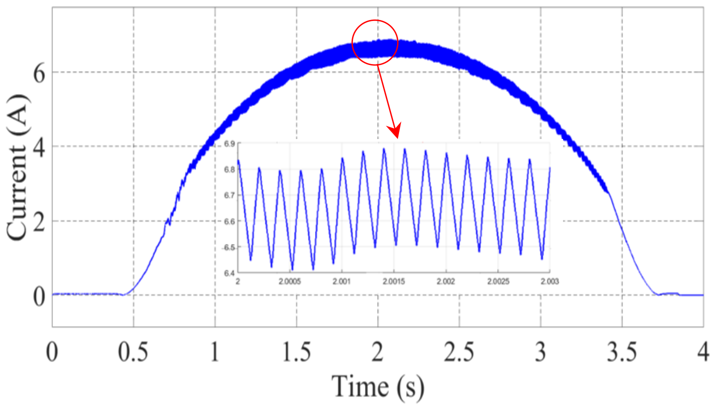

Fig. 8. Simulated PV output current waveform showing variations in irradiance under constant temperature conditions

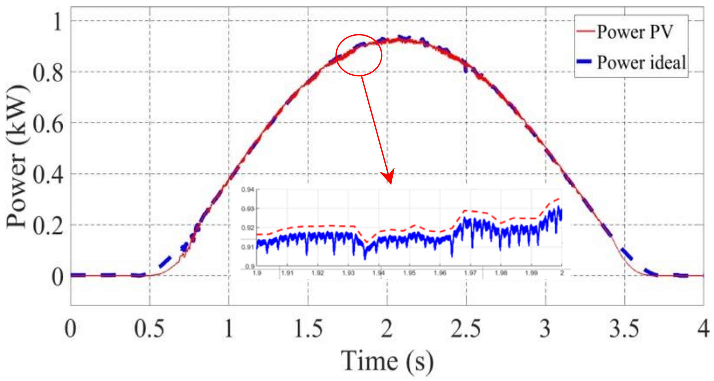

Fig. 9. Simulated PV output power waveform showing variations in irradiance under constant temperature conditions

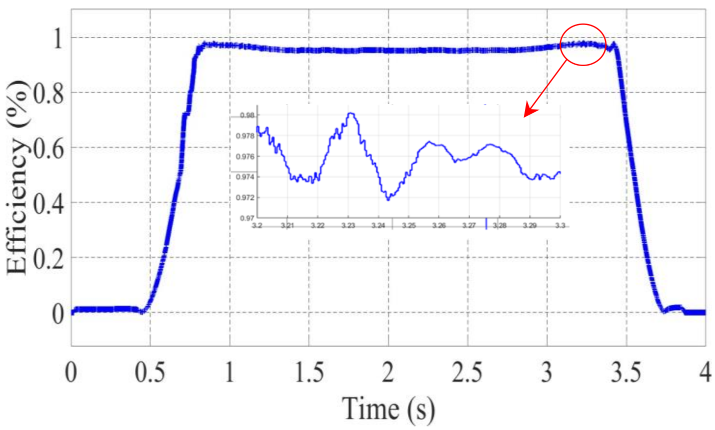

Fig. 10. Waveform of the simulated overall PV system efficiency illustrating variations in irradiance under constant temperature conditions

https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

5. CONCLUSIONS

In conclusion, PV panels undeniably remain one of the foremost alternative options for generating clean energy. However, the inherent nature of PV systems necessitates the incorporation of an effective MPPT algorithm to unleash their full potential. Without such algorithms, a PV system struggles to achieve maximum power output. This study presents and evaluated the P&O MPPT algorithm, managing a PV system coupled with a DC-DC boost converter. The P&O MPPT algorithm, designed to maximize the output power of the PV panel, effectively guides the system towards a point very close to the maximum available power from the PV panel source. The primary objective of this research was to simulate and assess the efficiency of the P&O MPPT algorithm when implemented in a PV system using MATLAB/Simulink. The case study, involving variable irradiance with a 'hill-shape' profile and fixed temperature, provided insights into the algorithm's performance under dynamic conditions. The simulation results underscore the efficacy of the P&O MPPT algorithm, demonstrating commendable performance even during irradiance variations. The maximum and mean overall efficiency, evaluated between panel and output power for the case study, reached an impressive 98%. By achieving this, the principal goal of this work, which is to investigate the power efficiency of the P&O MPPT algorithm for PV systems, has been successfully realized.

6. ACKNOWLEDGEMENTS

The authors would like to extend their sincere gratitude to the College of Engineering at Universiti Teknologi MARA (UiTM) and the Faculty of Electrical Engineering at Universiti Teknikal Malaysia Melaka (UTeM) for their continuous support and encouragement during this research project. Special thanks are also due to the Faculty of Sciences at Sidi Mohammed Ben Abdellah University in Morocco for their exceptional assistance and collaboration, which significantly enhanced the scope and impact of this study. The successful completion of this research would not have been possible without the contributions of these institutions, and for this, the authors are deeply appreciative.

7. CONFLICT OF INTEREST

The authors state that they have no competing interests with the funders and concur that this research was free from any financial, commercial, or self-benefiting conflicts.

8. AUTHORS' CONTRIBUTIONS

Nurfarah Ayuni Abdul Khani: Conceptualization, Methodology, Software Analysis and Writing-Original draft preparation. **Mohd Abdul Talib Mat Yusoh:** Curation of Literature and Data procurement & analysis. **Muhammad Iqbal Zakaria:** Supervision, Validation and Editing & Visualization. **Muhammad Nizam Kamarudin:** Editing & Visualization and Manuscript Proofreading. **Abdul Rahman A. An Emhemed:** Editing & Visualization and Validation.

9. REFERENCES

[1] D. Guiza, D. Ounnas, Y. Soufi, A. Bouden and M. Maamri, "Implementation of Modified Perturb and Observe based MPPT Algorithm for Photovoltaic System," in *1st Int. Conf. on Sustainable Renewable Energy Systems and Applications*, 2019. Available: https://ieeexplore.ieee.org/document/9182483.

https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

[2] CH. S. Kumar and G. Mallesham, "A new hybrid boost converter with P&O MPPT for high gain enhancement of solar PV system," *Materials Today: Proceedings*, vol. 57, no. 5, pp. 2262–2269, 2022. Available: https://doi.org/10.1016/j.matpr.2021.12.487.

[3] S. S. Dash and R. K. Dwibedi, "Design and Implementation of Perturb & Observe MPPT Algorithm under Partial Shading Conditions (PSC) for DC-DC Boost Converter by Simulation analysis," in *2020 Int. Conf. on Computational Intelligence for Smart Power System and Sustainable Energy*, 2020. Available: https://doi.org/10.1109/CISPSSE49931.2020.9212221.

[4] N. A. Yusri, S. N. H. M. Tarmizi, M. I. Zakaria, S. F. M. Hussein, and A. R. A. Emhemed, "Enhancing photovoltaic system efficiency through fuzzy logic-based maximum power point tracking," *International Journal of Electrical Engineering and Applied Sciences*, vol. 6, no. 2, pp. 43–52, 2023. Available: https://ijeeas.utem.edu.my/ijeeas/article/view/6173.

[5] M. Moutchou and A. Jbari, "Fast photovoltaic IncCond-MPPT and backstepping control, using DC-DC boost converter," *Int. J. of Electrical and Computer Engineering*, vol. 10, no. 1, pp. 1101–1112, 2020. Available: http://doi.org/10.11591/ijece.v10i1.pp1101-1112.

[6] A. I. M. Ali and H. R. A. Mohamed, "Improved P&O MPPT algorithm with efficient open-circuit voltage estimation for two-stage grid-integrated PV system under realistic solar radiation," *Int. J. of Electrical Power & Energy Systems*, vol. 137, p. 107805, 2022. Available: https://doi.org/10.1016/j.ijepes.2021.107805.

[7] A. B. Kebede and G. B. Worku, "Comprehensive review and performance evaluation of maximum power point tracking algorithms for photovoltaic system," *Global Energy Interconnection*, vol. 3, no. 4, pp. 398–412, 2020. Available: https://doi.org/10.1016/j.gloei.2020.10.008.

[8] M. I. Aziz Jafar, M. I. Zakaria, N. Y. Dahlan, M. N. Kamarudin, and N. El Fezazi, "Enhancing photovoltaic system maximum power point tracking with fuzzy logic-based perturb and observe method," *International Journal of Electrical and Computer Engineering*, vol. 14, no. 3, pp. 2386–2399, 2024. Available: https://doi.org/10.11591/ijece.v14i3.

[9] I. Al-Wesabi, Z. Fang, H. M. Hussein Farh, A. A. Al-Shamma'a and A. M. Al-Shaalan, "Comprehensive comparisons of improved incremental conductance with the state-of-the-art MPPT Techniques for extracting global peak and regulating dc-link voltage," *Energy Reports*, vol. 11, pp. 1590–1610, 2024. Available: https://doi.org/10.1016/j.egyr.2024.01.020.

[10] V. Bhan, A. A. Hashmani, and M. M. Shaikh, "A new computing perturb-and-observe-type algorithm for MPPT in solar photovoltaic systems and evaluation of its performance against other variants by experimental validation," *Scientia Iranica D*, vol. 26, no. 6, pp. 3656–3671, 2019. Available: https://doi.org/10.24200/sci.2019.54183.3635.

[11] N. A. Windarko, E. N. Sholikhah, M. N. Habibi, E. Prasetyono, B. Sumantri, M. Z. Efendi, and H. Mokhlis, "Hybrid photovoltaic maximum power point tracking of Seagull optimizer and modified perturb and observe for complex partial shading," *Int. J. of Electrical and Computer Engineering*, vol. 12, no. 5, pp. 4571-4585, 2022. Available: https://doi.org/10.11591/ijece.v12i5.pp4571-4585.

[12] Y. Zhu, M. K. Kim and H. Wen, "Simulation and analysis of perturbation and observation-based self-adaptable step size maximum power point tracking strategy with low power loss for photovoltaics," *Energies*, vol. 12, no. 1, pp. 92, 2019. Available: https://doi.org/10.3390/en12010092.

[13] J. Sahoo, S. Samanta and S. Bhattacharyya, "Adaptive PID controller with P&O MPPT algorithm for photovoltaic system," *IETE Journal of research*, vol. 66, no. 4, pp. 442–453, 2020. Available: https://doi.org/10.1080/03772063.2018.1497552.

[14] J. Ahmed, Z. Salam, M. Kermadi, H. N. Afrouzi and R. H. Ashique, "A skipping adaptive P&O MPPT for fast and efficient tracking under partial shading in PV arrays," *Int. Trans. on Electrical Energy Systems*, vol. 31, no. 9, pp. e13017, 2021. Available: https://doi.org/10.1002/2050-7038.13017.

https://doi.org/10.24191/esteem.v20iSeptember.1593.g1826

[15] Y. Xia, W. Wei, M. Yu and P. Wang, "Stability analysis of PV generators with consideration of P&O-based power control," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 8, pp. 6483–6492, 2019. Available: https://doi.org/10.1109/TIE.2018.2864695.

[16] A. Chellakhi, S. E. Beid and Y. Abouelmahjoub, "An improved adaptable step-size P&O MPPT approach for standalone photovoltaic systems with battery station," *Simulation Modelling Practice and Theory*, vol. 121, pp. 102655, 2022. Available: https://doi.org/10.1016/j.simpat.2022.102655.

[17] M. Mohammadinodoushan, R. Abbassi, H. Jerbi, F. W. Ahmed and A. Rezvani, "A new MPPT design using variable step size perturb and observe method for PV system under partially shaded conditions by modified shuffled frog leaping algorithm-SMC controller," *Sustainable Energy Technologies and Assessments*, vol. 45, pp. 101056, 2021. Available: https://doi.org/10.1016/j.seta.2021.101056.

[18] R. Palanisamy, K. Vijayakumar, V. Venkatachalam, N. R. Mano, D. Saravanakumar and K. Saravanan, "Simulation of various DC-DC converters for photovoltaic system," *Int. J. of Electrical and Computer Engineering*, vol. 9, no. 2, pp. 917–925, 2019. Available: https://doi.org/10.11591/ijece.v9i2.pp917-925.

[19] K. Ullah, M. Ishaq, F. Tchier, H. Ahmad and Z. Ahmad, "Fuzzy-based maximum power point tracking (MPPT) control system for photovoltaic power generation system," *Results in Engineering*, vol. 20, pp. 101466, 2023. Available: https://doi.org/10.1016/j.rineng.2023.101466.

[20] V. Bhan, S. A. Shaikh, Z. H. Khand, T. Ahmed, L. A. Khan, F. A. Chachar and A. M. Shaikh, "Performance evaluation of perturb and observe algorithm for MPPT with buck–boost charge controller in photovoltaic systems," *Journal of Control, Automation and Electrical Systems*, vol. 32, no. 6, pp. 1652–1662, 2021. Available: https://doi.org/10.1007/s40313-021-00781-2.

[21] M. R. Fazal, Z. Abbas, M. Kamran, M. N. Ayya and M. Mudassar, "Modified Perturb and observe MPPT algorithm for partial shading conditions," *Int. J. Renew. Energy Res*, vol. 9, no. 2, pp. 721–731, 2019. Available: https://doi.org/10.20508/ijrer.v9i2.9149.g7641.