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Comparison of Energy Obtained from Solar Panels in Partial Shading Condition Using Various MPPT Techniques

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Abstract

Partial shading conditions (PSC) create multiple peaks on the power–voltage (P–V) curve of photovoltaic (PV) systems, making it difficult for conventional Maximum Power Point Tracking (MPPT) algorithms to accurately identify the global maximum power point (GMPP). This study compares the performance of three MPPT techniques—Perturb and Observe (PNO), Global Maximum Power Point Detection (GMPPD), and the Four-Section (4S) method—by analyzing the electrical energy obtained during sudden changes in irradiance and shading. Experiments were conducted on two series-connected polycrystalline modules equipped with bypass diodes under three shading scenarios, with measurement data processed using an Arduino-based system. The novelty of this work lies in its experimental, energy-based comparison of PNO, GMPPD, and the recently developed 4S method under sequential irradiance transitions, providing a practical performance assessment that goes beyond instantaneous tracking evaluation commonly reported in previous studies. The results show that the 4S method significantly outperforms both PNO and GMPPD by providing faster tracking, lower computational demand, and superior accuracy under dynamic shading conditions. The total energy obtained using the 4S, GMPPD, and PNO methods was 4203.08 Wh, 3551.69 Wh, and 3091.60 Wh, respectively. These findings demonstrate that the 4S method offers the most efficient and reliable MPPT performance for PV systems operating under rapidly fluctuating environmental conditions.

Keywords: MPPT, Partial Shading GMPPD, 4S Method, Photovoltaic, Energy Comparison

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1. Introduction

Energy crisis has become a major global concern, and Indonesia is no exception as the country continues to rely heavily on fossil fuels to support industrial operations and daily activities. This dependence not only threatens long-term energy security but also contributes significantly to environmental degradation. Fossil fuel consumption releases harmful emissions that account for more than 65% of the increase in greenhouse gases, intensifying climate change and air pollution. To address these challenges, the transition toward clean and renewable energy sources is essential. Among the available alternatives, photovoltaic systems offer a promising solution because they generate electricity without producing emissions, supporting both environmental sustainability and national energy resilience [1], [2], [3], [4].

Photovoltaic systems can be integrated with the grid, either through decentralized power plants or large-scale power generation systems [5]. However, a major challenge in utilizing solar energy lies in its intermittent nature. The performance of a photovoltaic (PV) system is highly dependent on fluctuations in solar radiation, which directly affect the voltage and current at the Point of Common Coupling (PCC). These variations can degrade the overall power quality of the system and may cause inefficiencies or faults in electrical equipment [6]. Photovoltaic solar panels serve as key components in photovoltaic systems, functioning to convert solar energy into electrical energy [7], [8]. These panels display I–V (current–voltage) and P–V (power–voltage) characteristic curves that show the relationship between current, power output, and voltage. Under stable solar radiation, these curves reveal a single peak corresponding to the maximum power point at a particular voltage. solar radiation is often uneven because of shading caused by objects that block portions of the panels, creating Partial Shading Conditions (PSC).

Many researchers have investigated the characteristic curves of photovoltaic systems to determine the maximum power point. In the study presented by [9], photovoltaic arrays were analyzed through simulations to evaluate their parallel configurations. However, achieving more precise results requires conducting real-world experiments supported by measurement instruments. The Perturb and Observe (PNO) method is one of the most commonly used algorithms for Maximum Power Point Tracking (MPPT) in photovoltaic systems [10]. This algorithm continuously modifies the operating voltage or current of the PV system to locate the point where maximum power is produced. Although the PNO method is straightforward and easy to implement, it may perform less effectively under rapidly changing environmental conditions [11].

Earlier studies have attempted to prevent errors caused by local peaks in PV experiments under Partial Shading Conditions by applying the Global Maximum Power Point Detection Algorithm (GMPPD) [12]. However, this approach demands numerous iterations because it involves scanning all voltage values along the P-V curve to identify the true global maximum power point. To address this issue, further research was conducted to more efficiently determine the GMPP from PV experiments by dividing the voltage data range into four sections. Each section is examined to identify any peaks. The section with a detected peak is then further analyzed to determine whether the peak represents the global MPP or only the local MPP. By excluding the sections without peaks from further processing, computation is faster and the GMPP can be identified more quickly. The method is referred to as Four Section (4S) method [13].

Further verification is needed to determine how well the methods mentioned above perform when tracking the GMPP under rapidly changing sunlight conditions, including partial shading [14]. The novelty of this article lies in experimentally comparing the energy yield of three MPPT techniques—PNO, GMPPD, and the recently developed 4S method—under sequential irradiance transitions and differing partial shading levels. Unlike most previous studies that focus only on instantaneous power tracking accuracy, this work evaluates the actual electrical energy obtained from each method, providing a more realistic and application-oriented measure of MPPT performance. This study therefore offers new insight into the practical effectiveness of the 4S method relative to established approaches.

2. Methods

The photovoltaic system used in this study is composed of two polycrystalline photovoltaic modules connected in series. Each module with Pmax 20 WP, Voc 21.24 V, Isc 1,24 A, Vmpp 18 V and Impp1.11 A, is equipped with a bypass diode. The equivalent circuit of a PV module can be modeled using a parallel resistance, a series resistance, and an ideal diode current source [15], as shown in **Figure 1.**

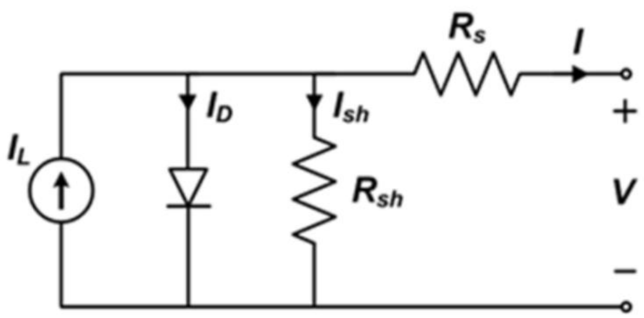

Figure 1. Equivalent Circuit of a Solar Cell

The direct current produced by the ideal current source corresponds to the amount of solar irradiance received by the PV module. The series and parallel resistances represent the leakage current along the cell path and the voltage drop up to the external terminal contacts. Based on this equivalent circuit, the output current can be expressed using the following equation:

$$I = I_{ph} - I_0 \left(e^{\frac{V+IR_s}{nV_t}} - 1 \right) - \frac{V+IR_s}{R_{sh}} \quad (1)$$

where:

- I = output current
- I_{ph} = photocurrent (proportional to irradiance)
- I_0 = diode saturation current
- R_s = series resistance
- R_{sh} = shunt (parallel) resistance
- n = diode ideality factor

$V_t = \frac{kT}{q}$= thermal voltage (k = Boltzmann constant, T = temperature in Kelvin, q = electron charge).

To conduct the testing, electrical measurements were carried out using the instruments shown in **Figure 2**. Halogen lamps were used to ensure stable irradiance for the photovoltaic modules. The photovoltaic modules were illuminated using halogen lamps positioned approximately 50–60 cm at the front of the panel in a symmetrical arrangement to ensure uniform light distribution. This setup produced irradiance levels of about 100 – 300 W/m², measured using a calibrated pyranometer placed in the same plane as the module. To maintain stable test conditions, a thermocouple was attached to the rear surface of the panel to monitor temperature, and airflow was provided around the module to prevent overheating; the lamp distance or operating time was adjusted when necessary to keep the module within typical operating temperature limits.

Current was measured using an INA129 instrumentation amplifier paired with a precision shunt resistor, providing high gain accuracy and low offset drift suitable for PV characterization. The current sensor was calibrated using a zero-offset procedure and a two-point reference measurement. The INA129 offers a gain accuracy of ±0.01%, bandwidth up to 120 kHz at unity gain, and low offset drift suitable for PV characterization. The PV output voltage was captured using a precision resistive voltage divider that scaled the panel voltage to the Arduino ADC input range, and its calibration was verified by comparing ADC readings with a reference multimeter.

These voltage and current signals were then transmitted to an Arduino UNO, where the various MPPT algorithms were programmed and executed to process the measurement data. All measurement data were then recorded and stored on a computer for further analysis.

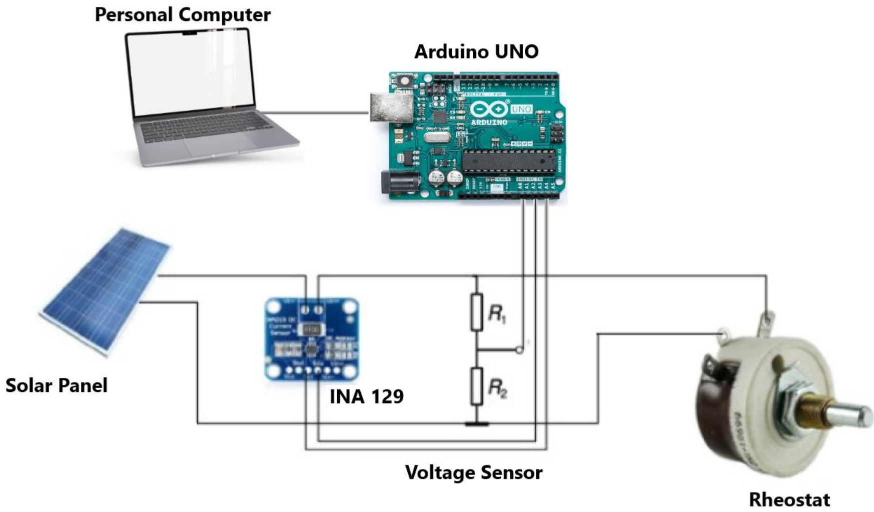

Figure 2. Measurement Instruments Recording The Photovoltaic Characteristic

One of the polycrystalline photovoltaic modules is covered to mimic the PSC, while the other one is left uncovered. The cover is set to get 10%, 50% and 70% shaded area of the module. The P-V curves obtained from experimental tests with various partial shading level are shown in **Figure 3**.

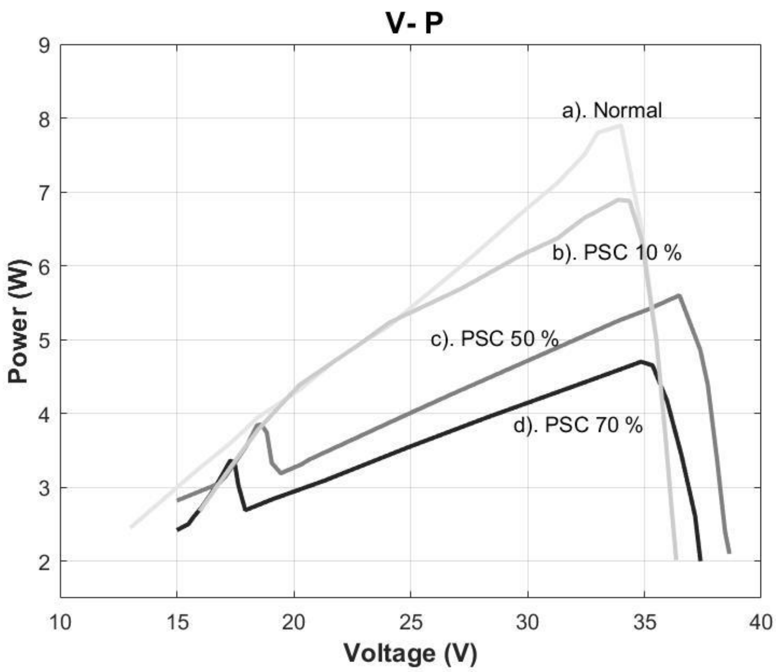

Figure 3. Various P-V Curve, a). Uniform irradiance, b). PSC 10%, c). PSC 50% and d). PSC 70%.

As shown in **Figure 3**, the P–V curve gradually changes as the shading level increases. When shading level is about 10% of the photovoltaic module, an inflection point forms on the curve, marking the beginning of a second peak. At this stage, the maximum power point is lower than that of the unshaded (0%) condition. When shading reaches 50% **Figure 3.** (c), the inflection point develops into a clear second peak, which becomes larger as the shaded area increases **Figure 3**. (d), illustrates the continued growth of this second peak as shading increases up to 70%. These multiple peaks caused by partial shading significantly complicate the MPPT process because the system can easily lock onto a lower local maximum instead of the true global maximum.

A good Maximum Power Point Tracking (MPPT) method is therefore essential in photovoltaic systems because it ensures that solar panels operate at the voltage and current combination that produces the highest possible power, even when the P–V curve contains multiple peaks. Since sunlight intensity, temperature, and shading constantly change, the natural operating point of the panels also shifts. Without MPPT, the system often runs away from the optimal point, resulting in significant energy losses. MPPT continually adjusts the operating point in real time, maximizing energy harvest throughout the day.

Under partial shading conditions, where multiple peaks appear on the power–voltage curve, a MPPT method should be able to help the system locate the true global maximum instead of getting stuck at a lower local peak. By consistently extracting the maximum available power, MPPT increases system efficiency, improves battery charging performance, and lowers the overall cost per unit of energy, making solar systems more economical and reliable.

The Perturb and Observe (PNO) method is a popular MPPT algorithm because it is simple and easy to implement. The algorithm of the method is shown in **Figure 4**. It works by slightly adjusting the voltage or duty cycle and observing whether the output power increases or decreases, then continuing or reversing the adjustment accordingly. However, PNO has several limitations: it tends to cause oscillations around the MPP, can get stuck at a local maximum under partial shading, and its performance is strongly influenced by the chosen perturbation step size.

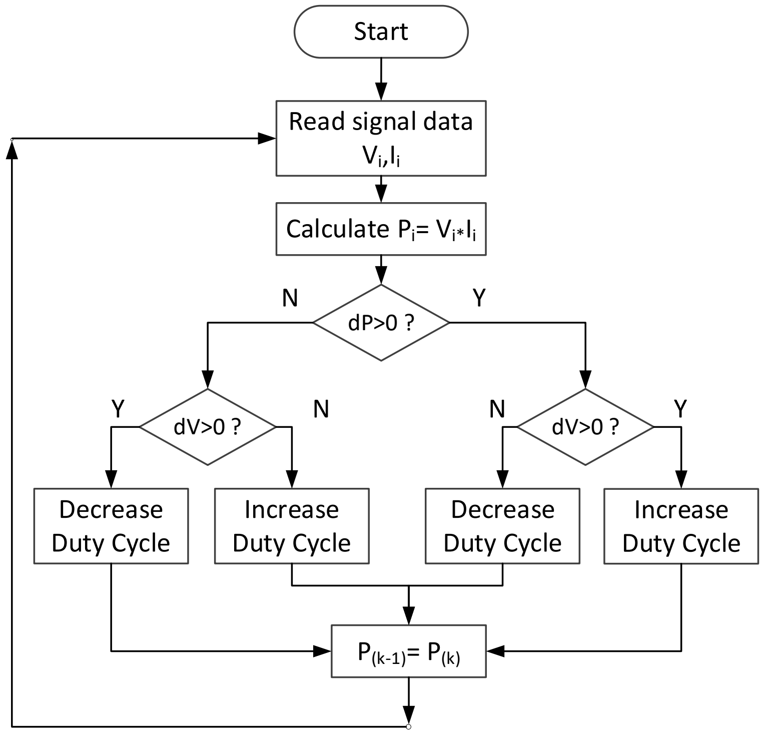

Figure 4. Flowchart of PNO Method

To avoid being trapped by the local peak, The GMPPD method [12] is designed to accurately identify the global maximum power point under partial shading by analyzing the PV array's power characteristics. Instead of relying on incremental changes like PNO, GMPPD reads sampled voltage and current data, calculates the slope of the P–V curve across all measured points, and evaluates these values to locate the true global peak, as shown in **Figure 5**. By examining the overall curve behavior—including shading-induced valleys, ridges, and rising power regions—it effectively distinguishes the highest-power point. This approach enables faster global searching, improved tracking accuracy under shading, and a reduced likelihood of settling at a local MPP.

The GMPPD method, although effective in identifying the global maximum power point under partial shading, has several limitations. Because GMPPD must read the full set of voltage and current data and evaluate the entire P–V curve, it can be computationally intensive and relatively slow, especially when implemented on low-cost microcontrollers. Its accuracy depends heavily on the density of sampling; insufficient data points may cause the algorithm to misinterpret curve slopes, while excessive sampling increases processing time. Additionally, GMPPD performs a full-curve analysis every time shading conditions change, which can lead to delays in rapidly fluctuating environments.

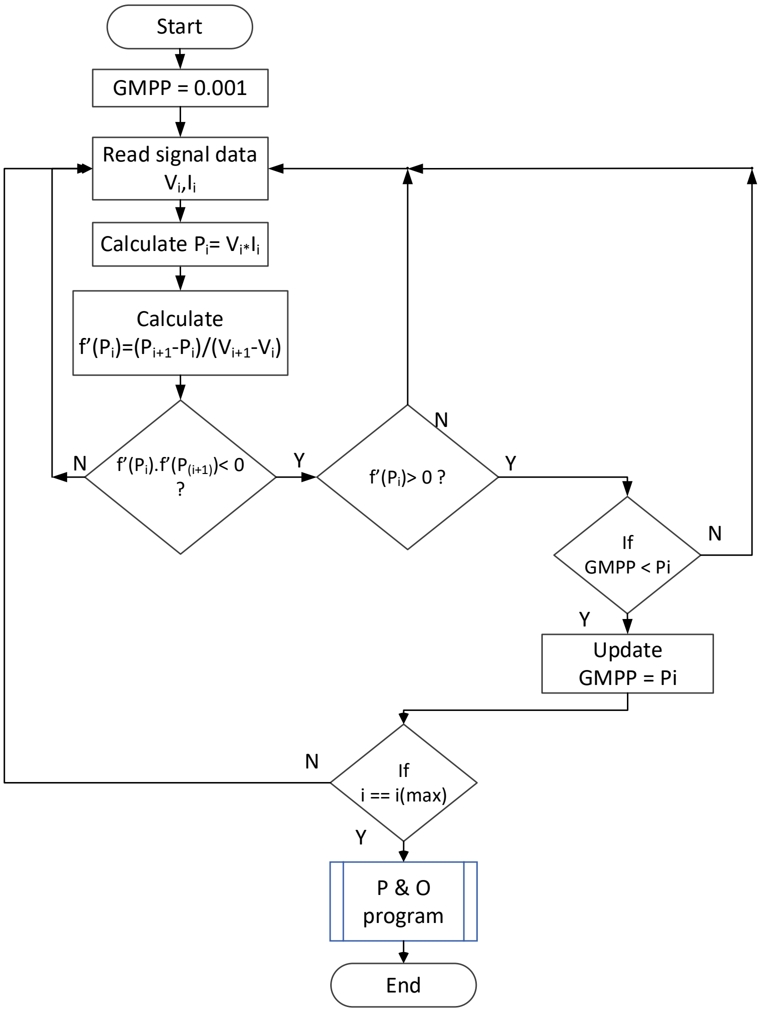

Figure 5. GMPPD Method

To improve the tracking performance, the Four Section (4S) method is developed. The algorithm shown in **Figure 6.** addresses GMPPD limitations by dividing the operating voltage range into four strategic segments and evaluating only the most promising section instead of scanning the entire curve.

The 4S method operates through the following procedure:

a) The voltage or PWM range of the P–V curve is first split into four equal segments.
b) For each selected segment, the slope f′(x) is computed at both its starting and ending points.
c) If the slope at the beginning of the segment is positive ($f'(x) > 0$) and becomes negative at the end ($f'(x) < 0$), the segment is identified as potentially containing a peak.
d) Segments that do not satisfy this condition are disregarded.
e) The process is then repeated by further subdividing any segment that is flagged as containing a possible peak.

Using these steps, the 4 sections method can be described in the flowchart in **Figure 6.** below.

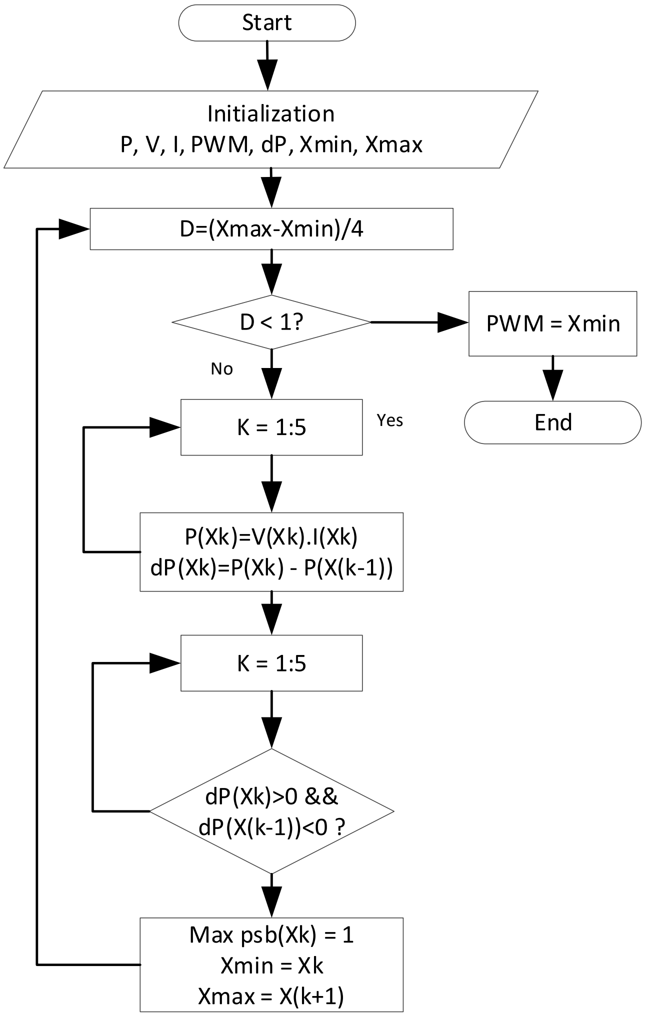

Figure 6. 4S Method

To get more details about how the 4S Method works, the tracking process of 4S method implemented to PSC 50 % is shown in **Figure 7** below.

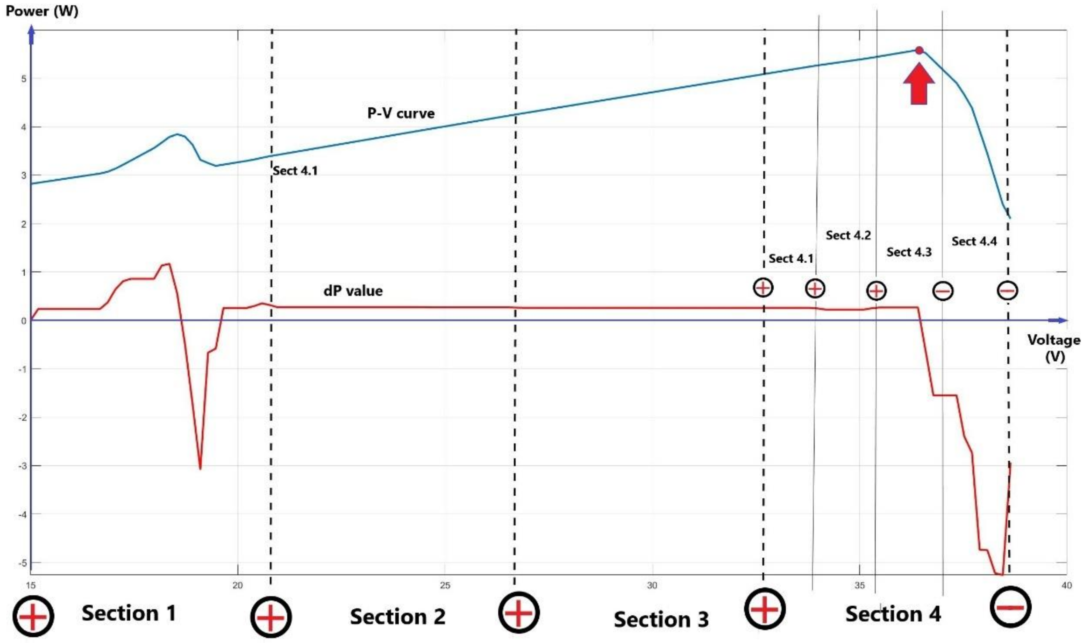

Figure 7. The Tracking Process of 4S Method

Figure 7 shows the sections 1, 2, 3, 4 which has been marked as positive when the dP of the section border is greater than 0. Otherwise, the border will be marked as negative. The section that met the criteria is only section 4. Therefore, the algorithm is repeated at Section 4. Section 1, 2, 3 are ignored as the borders of the section do not meet the criteria, so this will reduce time required to do the tracking process. In Section 4, the algorithm divides the area to be 4 smaller sections of the same size and check the value of dP at the borders. Every border is then checked to obtain that the 3rd section of Section 4 has the possibility of the peak. The process is then repeated to obtain the data point that has the maximum value of the power.

This targeted approach reduces computation time, lowers sampling requirements, and accelerates the search for the global peak. By narrowing the search region early in the process, the 4S method achieves faster tracking with less processing burden, making it more suitable for real-time MPPT applications and embedded systems. As a result, the 4S method offers greater efficiency, quicker response to shading changes, and improved overall reliability compared to GMPPD.

3.Results and Discussion

The performance of MPPT methods can be evaluated by observing how much energy each algorithm is able to extract during sudden changes in irradiation and shading levels. Solar conditions often fluctuate rapidly due to moving clouds, partial obstructions, or environmental shifts, causing the P–V curve to change within seconds. By measuring the energy harvested during these transitions, researchers can assess how quickly and accurately each MPPT method responds to dynamic conditions. Algorithms that react too slowly or incorrectly may fail to track the global maximum power point, leading to significant energy loss during these critical periods.

Performance comparison based on energy yield also highlights the strengths and weaknesses of each algorithm, providing insight beyond static efficiency measurements. Methods like PNO may struggle with local maxima, while GMPPD may experience delays due to full-curve evaluation, and newer techniques such as the 4S method may adapt more effectively to rapid changes. Calculating the actual energy harvested during sudden shading or irradiance shifts allows for a fair and practical assessment of tracking speed, stability, and reliability. This comparison is essential for selecting the most efficient MPPT strategy for systems operating under highly variable environmental conditions.

The test is designed by implementing 3 different scenarios sequentially to each MPPT method and measure the energy yielded by each method. Each scenario represents uniform irradiation P-V characteristic, partial shading condition 50% and partial shading condition 70% respectively. The P-V characteristic for each scenario has been shown in **Figure 3**.

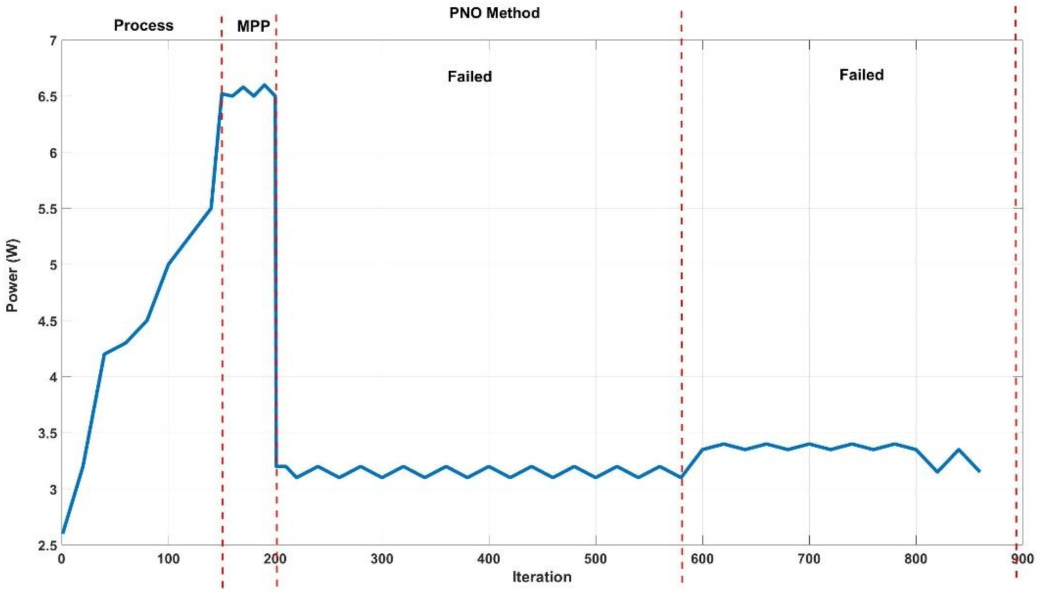

Figure 8. Power obtained by PNO

Figure 8 shows the performance of PNO method to track the MPP under various irradiations. For scenario 1 (uniform irradiation condition), it successfully tracked the MPP, but for scenario 2 and 3 which represent PSC 50% and 70%, The method was trapped to a local peak and therefore failed to track the MPP.

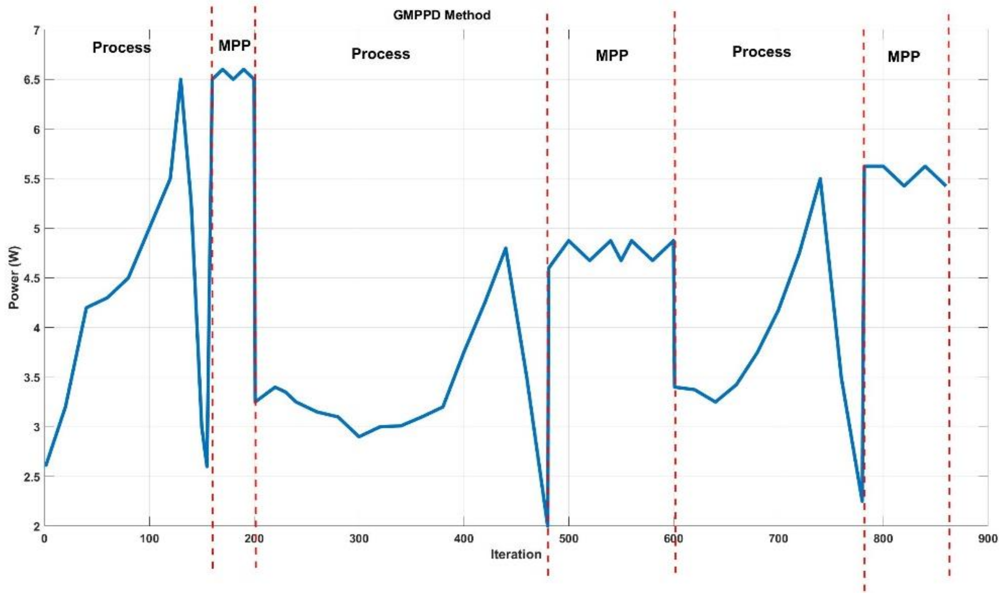

Figure 9. Power obtained by GMPPD

GMPPD method is then tested to track the MPP under scenario 1 to 3, as shown in **Figure 9** For all the scenarios, it successfully tracked the MPP. The extra peaks in Scenario 2 and 3 can be identified as local peaks and therefore ignored by the method. However, the algorithm has to read all the voltage data of the P-V curve, so the tracking speed is relatively slow. For example, when GMPPD has got the MPP for uniform irradiation condition (Scenario 1), it still has to keep doing the tracking process completely before running at the MPP.

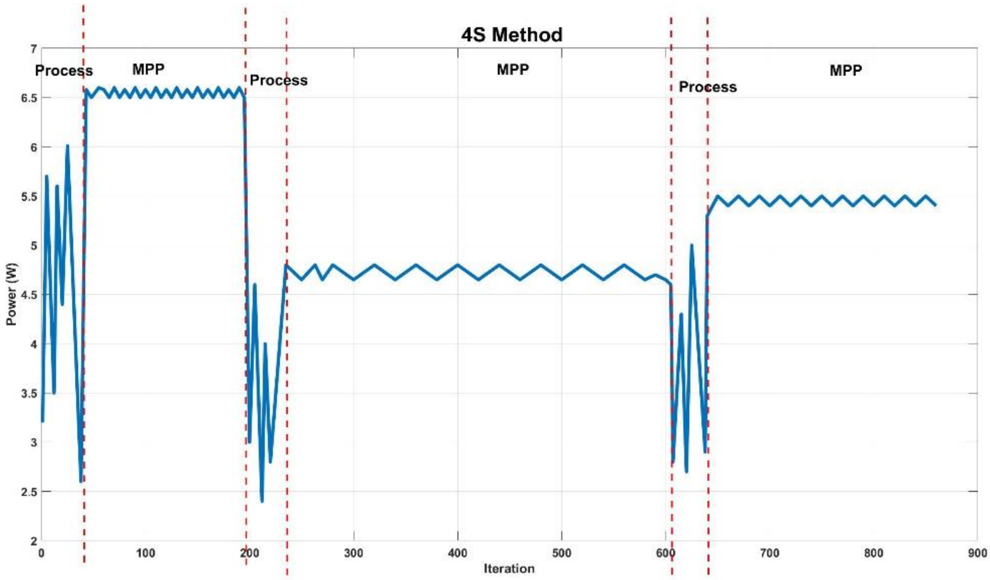

Figure 10. Power obtained by 4S Method

The performance of 4S method under the test is shown in Figure 10. It is clear that the method needs only few iterations to track the global maxima, and successfully avoid the local peaks. The method identifies the MPP earlier than the GMPPD and PNO method, therefore it can obtain more energy than other methods.

3.1 Result

To present the results clearly, this section summarizes the key findings obtained from the experimental testing of the three MPPT algorithms—PNO, GMPPD, and the 4S method—under different partial shading conditions. The results are shown in Tabel 1.

Tabel 1. Energy obtained by MPPT Method

Method	Energy obtained (Wh)
PNO	3091.60
GMPPD	3551.69
4S	4203.08

In this study, the performance of each MPPT method was evaluated by observing how effectively it tracked the maximum power point during sudden changes in irradiation and shading levels. Since the P–V curve deformed significantly under PSC, the results highlight the ability of each algorithm to detect and maintain the global maximum power point. Figure 8, 9, 10 illustrate the tracking performance of PNO, GMPPD, and 4S methods respectively, showing how each algorithm responds when multiple power peaks are present. These figures represent typical behavior observed throughout the experiment and allow direct comparison of tracking accuracy, responsiveness, and susceptibility to local maxima.

To quantify performance in a practical manner, the total electrical energy obtained from each method was calculated by integrating the power over time for all three test scenarios. This approach provides a more realistic indicator of MPPT efficiency than instantaneous power measurements alone. The energy values obtained are summarized in **Tabel 1**, which clearly shows the differences in performance among the three algorithms. The table serves as the main reference point for comparing the overall capability of the MPPT methods in extracting usable energy under dynamic and challenging shading conditions.

Overall, this section presents the essential findings of the study using the most representative figures and tables. These results form the foundation for the discussion that follows, where the implications, strengths, and limitations of each MPPT method are analyzed in detail.

3.2 Discussion

The results of this study demonstrate clear performance differences among the three MPPT methods when operating under sudden variations in partial shading. The PNO method, while simple and effective under uniform conditions, consistently failed to maintain tracking accuracy in PSC scenarios. As shown in **Figure 8**, the algorithm successfully reached the MPP in Scenario 1 but was unable to escape local peaks in Scenarios 2 and 3. This confirms the limitation of PNO in dealing with multiple peaks on the P–V curve, which leads to reduced harvested energy and unstable tracking behavior when shading intensifies.

The GMPPD method improved the tracking accuracy significantly by evaluating the entire P–V curve, allowing it to detect the global maximum power point even in the presence of multiple peaks **Figure 9**. This method's robustness under PSC is evident in its ability to ignore local maxima and converge on the correct peak. However, the energy results show that GMPPD still underperforms compared to the 4S method. The delay caused by full-curve scanning limits its responsiveness, especially during rapid irradiance transitions. As a result, GMPPD spends more time in non-optimal operating regions, which explains its lower energy output relative to the 4S approach.

The 4S method demonstrated the highest efficiency and fastest convergence among the algorithms tested. By dividing the voltage range into four strategic segments and narrowing the search domain early, the method quickly isolates the region containing the global peak. This leads to significantly fewer iterations and faster stabilization at the MPP, as shown in **Figure 10**. The energy values further confirm this advantage: the 4S method outperformed both PNO and GMPPD by a substantial margin, achieving 4203.08 Wh—approximately 18% more than GMPPD and 36% more than PNO. This performance shows that selective scanning not only reduces computational load but also improves real-time adaptability, which is essential under fluctuating shading conditions.

Conventional perturb-and-observe (PNO) algorithms are known to be simple and effective under uniform irradiance but prone to getting trapped at local maxima when the P–V curve becomes multi-modal under partial shading; this limitation and the resulting loss of harvested energy have been documented in multiple reviews and comparative studies [16]. In contrast, GMPP-oriented approaches that scan or analyze the full P–V curve are designed to locate the true global maximum and therefore provide more reliable tracking under PSC, but they typically require denser sampling or iterative scanning which increases computation time and delays convergence in rapidly changing conditions [17]. Comparative studies that measure energy yield (rather than only instantaneous tracking metrics) report that GMPP-capable methods improve overall extraction but can still lose energy when their full-curve procedures are slow relative to weather transients [18].

Segmentation or selective-scanning strategies (such as the Four-Section (4S) approach used here) aim to combine the best of both worlds by reducing the search domain early and avoiding exhaustive full-curve scans. Recent works on converting multi-peak curves into effectively single-peak problems, and on region-based/global-search hybrid strategies, support the idea that targeted searches reduce computational burden while preserving GMPP detection capability, improving real-time energy capture under dynamic shading patterns [19]. Our experimental results corroborate these findings and extend them by providing direct energy-integration comparisons: the 4S implementation [13] attains higher total harvested energy than both PNO and a GMPPD-style full-curve method in sequential irradiance/shading tests, demonstrating the practical advantage of segmentation-based strategies in real operating conditions.

Overall, the findings support the conclusion that MPPT algorithms must balance accuracy and computational efficiency to perform well under PSC. While PNO lacks the capability to differentiate between local and global peaks, and GMPPD provides higher accuracy but suffers from slow response due to full-curve scanning, the 4S method successfully bridges this gap by offering rapid GMPP detection with minimal computational burden. The specific novelty of this article lies in demonstrating, through real-time experimental measurements and energy-integration analysis, that the 4S method yields significantly higher total harvested energy compared with both PNO and GMPPD under sequential irradiance transitions and multiple partial shading levels. This energy-based evaluation provides practical evidence of the 4S method's superiority in real operating conditions, going beyond the instantaneous tracking comparisons typically reported in previous studies.

4. Conclusion

This study evaluated the performance of three MPPT algorithms—PNO, GMPPD, and the 4S method—under varying partial shading conditions. The experimental results confirm that partial shading significantly alters the P–V curve, creating multiple peaks that challenge conventional tracking techniques. The PNO algorithm, although simple, struggles to avoid local maxima, while GMPPD improves accuracy but requires full-curve scanning that increases computation time. The 4S method demonstrates the best overall performance by efficiently narrowing the search region and rapidly identifying the global MPP with lower processing demand. Energy comparison results show that the 4S method yields the highest energy output at 4203.08 Wh, outperforming GMPPD and PNO by a substantial margin. Therefore, the 4S method is the most effective MPPT strategy for PV systems experiencing rapid changes in shading and irradiance.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

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