Optimum MPPT technique for reconfiguring the photovoltaic array under partial shading failure

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***Abstract*—Partial shading (PS) considerably restricts photovoltaic (PV) systems, requiring extraction of the global maximum power point (GMPP). This persistent challenge engenders continuous fluctuations in the maximum power point (MPP) and demands utmost attention. In this regard, this paper presents a novel hybrid scanning technique and a Perturb and Observe (P&O) algorithm meticulously designed to accurately track the PV array's GMPP encountering PS, non-uniform dust deposition, or any common failures. Furthermore, it serves as an efficient tool that operates in tandem with the dynamic reconfiguration approaches. Extensive simulation tests were carried out using MATLAB Simulink software, while the validation and verification processes were conducted using an integrated Arduino board. Consequently, the simulation results exhibit outstanding accuracy and stability.**

***Index Terms*—Photovoltaic Array, partial shading, scanning, P&O, Failures, GMPPT.**

I. INTRODUCTION

In recent years, the worldwide manufacturing and commercialization of photovoltaic (PV) panels have experienced a remarkable surge. This significant trend primarily stems from the failure of traditional energy sources to comply with stringent greenhouse-gas emission mitigation [1]. Consequently, photovoltaic energy plays a crucial role, exhibiting broad applicability across multiple sectors and making a substantial contribution to the advancement of sustainable and clean energy solutions. To ensure the efficient utilization of photovoltaic energy, it is imperative to address the various challenges associated with its operation. By effectively managing these issues, one can unleash the full potential of photovoltaic technology, thereby achieving optimal performance. In this context, reconfiguration, floating photovoltaic plants, global maximum power point tracking, solar trackers, cooling systems, and cleaning techniques are the foremost methodologies applied to enhance the output efficiency of PV systems [2]. This investigation aims to provide substantial contributions to the advancement of photovoltaic systems by shifting its focus towards the rigorous exploration and implementation of GMPPT in the presence of anomalies, mainly under partial shading conditions, which may significantly exert a profound influence on the electricity output [3]. Consequently, the power-voltage (P-V) characteristic curve demonstrates a distinct profile, marked by the emergence of multiple peaks, thereby rendering the extraction of GMPP more challenging. The literature consistently emphasizes different MPPT control strategies based on their distinct operating principles and levels of complexity, which ultimately yield varying degrees of effectiveness. Conventional MPPT methods can reach the MPP exclusively under uniform insolation conditions. Hence, conventional MPP tracking becomes ineffective due to the existence of several peaks in the P-V curve. Although several GMPPT techniques have been developed to overcome the limitations of conventional MPPT by accurately identifying the true maximum power point among multiple peaks [4]. Through a rigorous literature review encompassing GMPPT techniques, a meticulous examination revealed the ubiquitous recognition that accuracy, stability, and convergence speed remain persistent issues across all methodologies [5]. The classification of GMPPT methods encompasses optimization-based algorithms, hybrid methodologies combining several optimization algorithms, and alternative approaches, such as curve fitting and fuzzy controllers [6]–[8]. Moreover, considerable attention has been directed toward the Distributed Maximum Power Point Tracking (DMPPT) method. Undoubtedly, the integration of the DMPPT technique into photovoltaic (PV) systems effectively mitigates mismatch failures. DMPPT entails a multimodule PV configuration, where each module is equipped with a dedicated switching converter that facilitates efficient MPPT operations. However, such an approach is not economically viable, particularly when considering large-scale PV plants [9]. Numerous scholars have utilized MPPT to identify and diagnose prevalent anomalies, such as open circuits, short circuits, partial shading, and degradation, owing to its practical attributes. For instance, the momentary change in the rightmost MPP voltage can be used effectively to differentiate between the partial shading conditions [10]–[12]. This paper introduces an improved GMPPT approach that combines scanning and upgraded perturbation and observation techniques to achieve PV array's maximum power. Further, this approach complements the reconfiguration process by accurately identifying the GMPP and maintaining optimal power tracking throughout the day. Consequently, the integration of PV scanning with enhanced P&O methodologies demonstrates tremendous potential for adapting to faulty operating conditions. The investigation reported in this paper is divided into four sections to clearly outline the main purpose:

- The second section is devoted to presenting PV panel behavior under partial shading conditions, alongside an elucidation of the specific scenarios taken into consideration.
- The third section highlights the approach implementation, as well as a discussion of acquired results.
- Fourth section introduces a brief conclusion along with certain recommendations for subsequent investigations.

II. PV PANEL BEHAVIOR UNDER PSC AND SUGGESTED SHADING SCENARIOS.

A. *PV panel behavior under PSC*

Throughout the year, the uniform illumination of the solar array by sunlight is a rare occurrence owing to various constraints, including partial shading and dust accumulation. Consequently, these factors hinder the direct exposure of photovoltaic cells to sunlight, resulting in the emergence of multiple peaks in the power-voltage (P-V) curve. Among these peaks, the largest corresponds to the global maximum power point, whereas the others represent local maxima [4], [13]. Fig 1 depicts the P-V curve, showing its distinctive multi-peaks. Namely, the PV array utilized in this study comprised 12 PV units strategically arranged into three parallel-connected strings. Each string consists of four PV modules interconnected in series. Fig 2 provides further detail on the PV array. Moreover, the photovoltaic module properties under standard test conditions (STC) are listed in Table I.

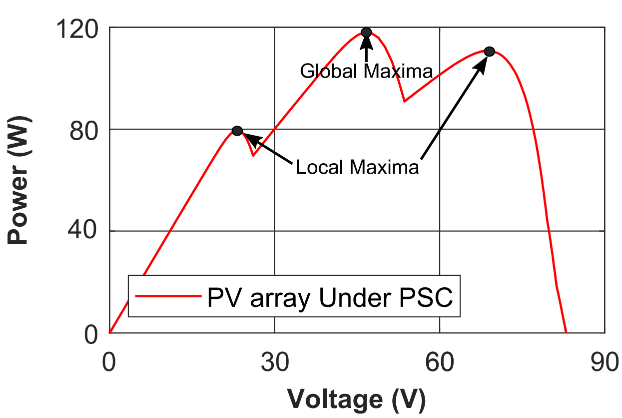


Fig. 1: PV array's P-V curve under partial shading conditions.

B. *Suggested Partial Shading Models*

This section explicitly describes various circumstances that may occur during the dynamic reconfiguration process. The scenarios were systematically classified into two distinct groups of partial-shading patterns. The first group focuses on the shading pattern observed in typical operational scenarios. In this case, a PV array is subjected to four randomly selected shading patterns, which correspond to the standard models published in the literature, including short and wide, short and narrow, tall and wide, and tall and narrow [9]. A graphical representation of these patterns is shown in Fig 3.

The second cluster of shading patterns manifests predominantly during the reconfiguration process. The first scenario involves the deliberate manipulation of the irradiance contrast experienced through the PV array, where the PV curve retains its distinctive shape, while the global maximum power point value evolves progressively according to the solar irradiance profile throughout the day. In this instance, the shaded panels are subjected to a linear increase in irradiance ranging from 200 W/m^2 to 1000 W/m^2. Fig 4 illustrates the P_V curve corresponding to the first scenario of the second category of the partial shading patterns. In contrast, the second scenario involves dynamic topology reconfiguration, leading to a significant distortion in the shape of the PV curve and, consequently, a substantial shift in the global maximum power point value. Fig 5 shows the PV curve of the series-parallel and total cross topologies, along with its basic interconnection schemes.

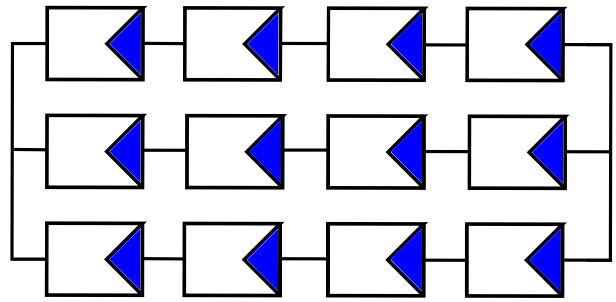


Fig. 2: Proposed PV array configuration .

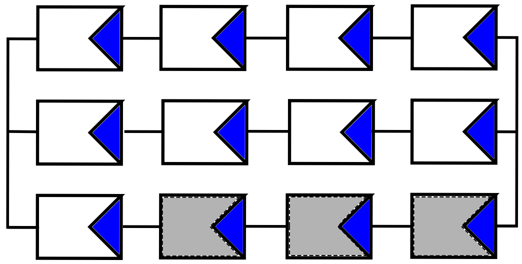
TABLE I: TDC-P20-36 polycrystalline PV module features at STC.

Characteristics	Values
P_{max} Maximum Power	20 W
V_{mpp} Voltage at Maximum Power	17.2 V
I_{mpp} Current at Maximum Power	1.17 A
V_{oc} Open Circuit Voltage	21.2 V
I_{sc} Short Circuit Current	1.28 A
Operating temperature	$-40°C$ to $85°C$
Dimension (m)	$0.48 \times 0.35 \times 0.017$
Number of Cells	36

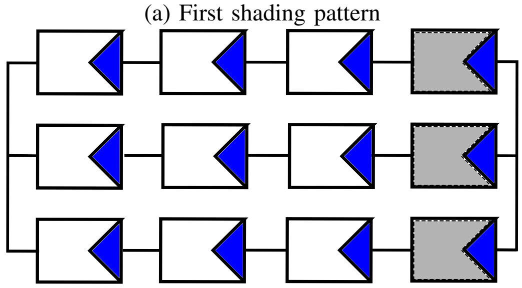
III. PROPOSED GMPPT TECHNIQUE

A. *Proposed GMPPT concept*

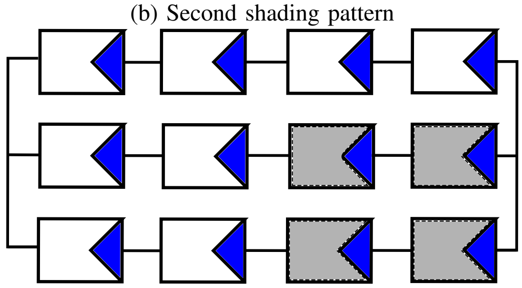
The current investigation deploys the GMPPT methodology, a hybrid technique that combines scanning and an enhanced P&O approach. The scanning strategy involves a meticulous process of plotting and analyzing the P-V curve of the photovoltaic system to precisely identify and select the global peak.



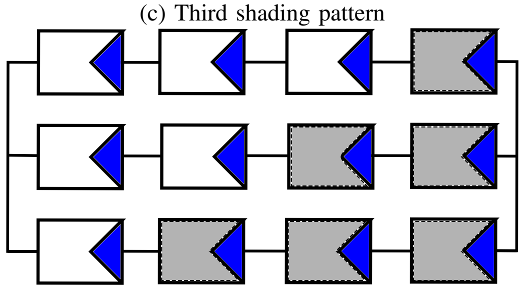
(a) First shading pattern



(b) Second shading pattern



(c) Third shading pattern



(d) Fourth shading pattern

Fig. 3: First cluster of partial shading models.

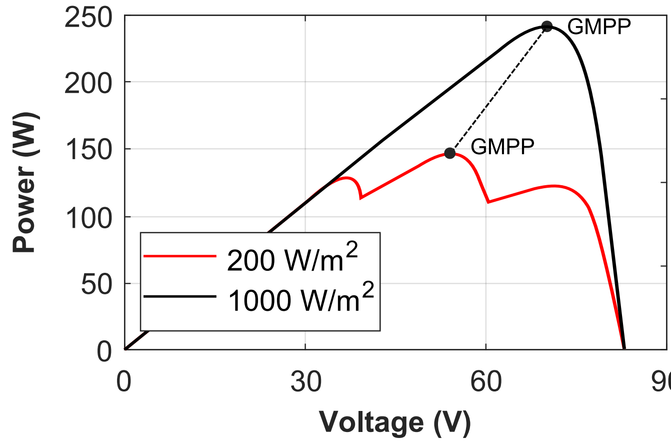


Fig. 4: P_V curves representing the second scenario of the second partial shading category.

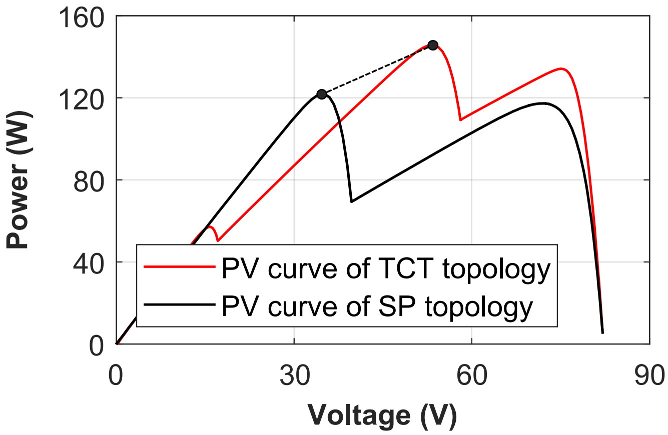
While the improved P&O technique effectively initiates tracking of the GMPP using the value identified during the scanning approach, allowing its gradual tracking, which reflects the solar irradiance profile throughout the day to effectively manage its fluctuations. In the event of sudden anomalies, such as full or partial shading, open circuit, short circuit, or during the dynamic reconfiguration process, the algorithm systematically restarts the PV curve scanning procedure, ensuring continuous GMPP tracking. Fig 6 shows the flowchart of the proposed algorithm.

B. Implementation of the proposed approach on MATLAB software.

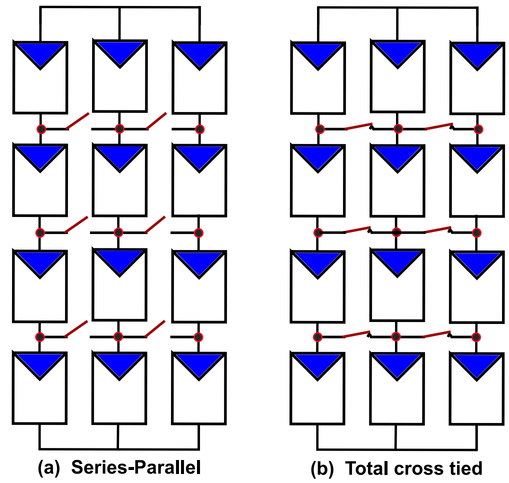
The primary aim of this deployment is to conduct an in-depth assessment of the effectiveness, reliability, and robustness of the GMPPT methodology to achieve optimal GMPP. This assessment aims to enable adaptive operations in the presence of failures and ensure the effectiveness of dynamic reconfiguration techniques, thus contributing to the overall optimization of the PV system. The Model in the Loop (MIL), Software in the Loop (SIL), and Processor in the Loop (PIL) validation tests were meticulously performed using MATLAB Simulink along with the Arduino board, utilizing a performant laptop equipped with AMD Ryzen 16-Core processor running at $4.5GHz$ and $64GB$ of RAM. This configuration ensures efficient and precise simulations. Fig 8 provides a clear visualization of the validation cycle and offers insights into the process. The objective of this evaluation is assessed through the incorporation of all the aforementioned shading models. Well-lit PV modules maintain a consistent irradiance level of $1,000\ W/m^2$. In contrast, shaded panels are subjected to a steady irradiance of 200 W/m^2. Furthermore, for the shading model related to the daily irradiation profile, the irradiation level ranges from 200 W/m^2 to $1,000\ W/m^2$. The implementation of the improved scanning procedure in the Matlab software adheres to the following meticulous guidelines.

- **Step 01**: Launching the P_V curve scan while progressively increasing the duty cycle value from the minimum to the maximum value [0.05, 0.85].
- **Step 02**: Indicates the maximum power output and its corresponding duty cycle, respectively.
- **Step 03**: Apply enhanced P&O approach based on the corresponding duty_cycle value, voltage, and power identified in the second step.
- **Step 04**: Check if a specific power threshold has been surpassed. If affirmative, reset the variables and restart the scanning procedure.

Algorithm 1 provides the pseudocode of the proposed technique.



(a) P_V curves



(b) Basic Interconnection Schemes

Fig. 5: The PV Curve of Series-Parallel and Total Cross Topologies with their Basic Interconnection Schemes.

Algorithm 1 Improved GMPPT scanning technique

Require: **V** $(voltage)$, **I** $(current)$
Ensure: Appropriate **D** $(duty\_cycle)$
▷ *******Initialisation*********
$Delta \leftarrow 0.01$, dc(62,1), u, p(62,1), best_duty(62,1), best_vol(62,1), $count \leftarrow 1$
▷ ****Scanning Procedure****
while $((count \leq 1)$ & $(count \geq 40))$ **do**
  D=Dc; count=count+1;
end while
if $((u \leq 1)$ & $(u \geq 62)$ & $(V \times I \geq p(u)))$ **then**
  $p(u) = V \times I$; $best\_duty(u) = Dc$; $best\_vol(u) = V$;
else if $u = 63$ **then**
  $[P_old, i] = max(p)$; $D = best\_duty(i)$;
  $V\_old = best\_vol(i-1)$; $Dold = D$;
▷ **Improved P&O Procedure**
else if $u = 64$ **then**
  $P = V \times I$; $dV = V - V_old$; $dP = P - Pold$; $M = abs(dP)$;
  if $(M < 0.01)$ **then**
    $D = Dold$;
  else
    if $dP < 0$ **then**
      if $dV < 0$ **then**
        $D = Dold - 0.001 \times M$;
      else
        $D = Dold + 0.001 \times M$;
      end if
    else
      if $dV < 0$ **then**
        $D = Dold + 0.001 \times M$;
      else
        $D = Dold - 0.001 \times M$;
      end if
    end if
  end if
end if

IV. Result and Discussion

An exhaustive simulation study is conducted to rigorously evaluate the effectiveness of the proposed algorithm under transient irradiation conditions. Given the challenge of assessing every non-uniform insolation scenario, this investigation focussed on utilizing the two distinct partial shading models as illustrated in Figs 3, 4 and 5 as the premise for testing and analysis. The results of the initial test depicted in Fig 9 showcase the effective maximum power point tracking through the application of four distinct partial shading patterns. The outcomes of each scenario are delineated into two integral parts: first, the scanning process, and second, the identification of the GMPP accompanied by the utilization of the P&O approach for robust power extraction management. The scanning technique is promptly activated upon the detection of an inexplicable power drop by the P&O approach, indicating potential anomalous conditions. It is worth highlighting that the scanning time exhibited exceptional efficiency, overcoming the techniques reported in the literature. The results of the second cluster of partial shading conditions are visually depicted in Fig 9. These results specifically pertain to dynamic reconfiguration strategies, which entail the imperative task of extracting maximum power during the panel's arrangement phase alongside the astute selection of appropriate interconnection schemes. Fig 10 unequivocally demonstrates the effective attainment of maximum power through the implementation of the serial-parallel topology (SP) and the total cross configuration (TCT). Notably, the transition between these two topologies is accurately detected, proving the effectiveness of the implemented Perturb and Observe (P&O) algorithm. Fig 11 clearly shows the results of the second scenario of the second partial shading group, which represents a gradual shift in irradiation. The proposed methodology perfectly tracks the maximum power of the photovoltaic array, demonstrating its utility. Dynamic growth of power is seen particularly in the interval $[1s,\ 2s]$ when specific photovoltaic units get irradia-

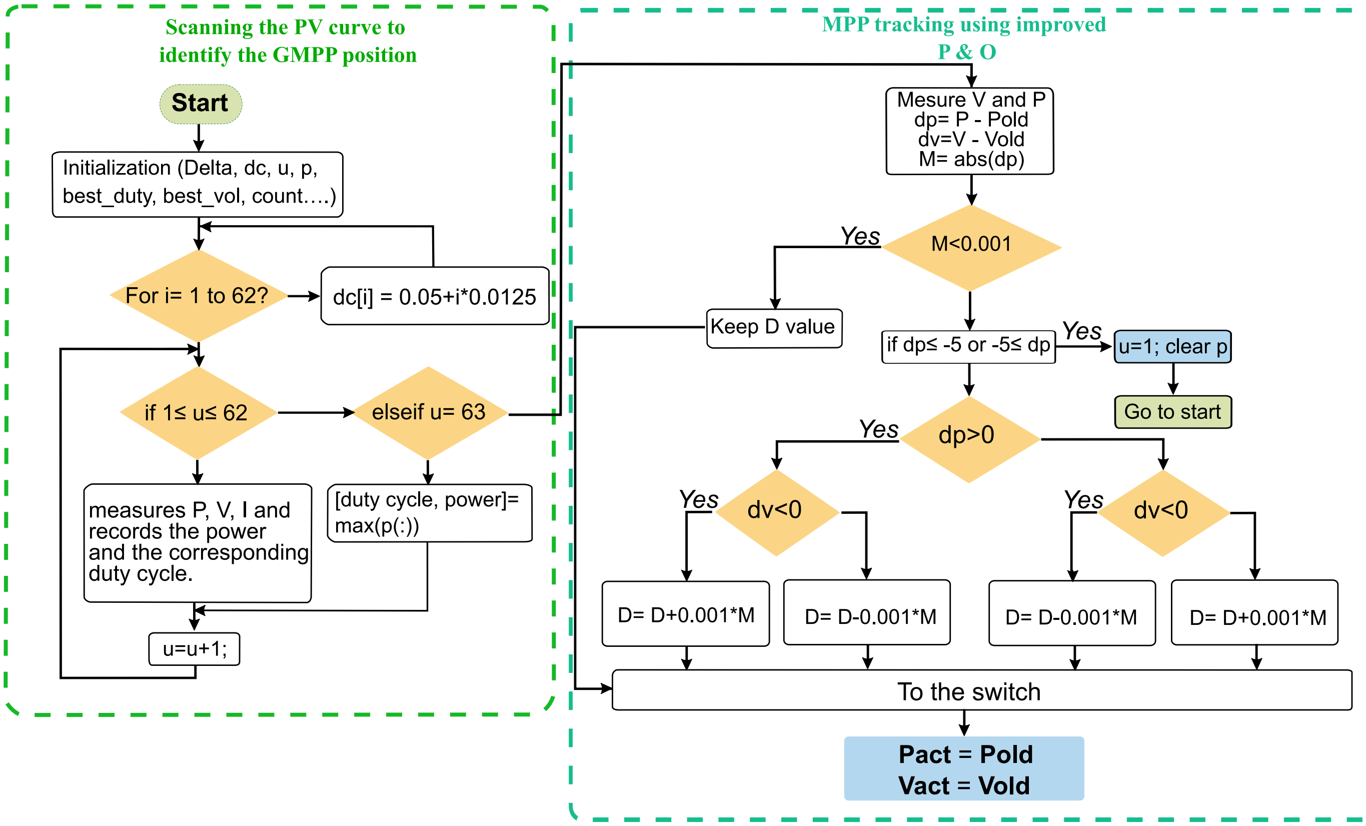


Fig. 6: Flowchart of the proposed GMPPT technique.

tion varying from 200 W/m^2 to 1000 W/m^2. Following these extensive deliberations and the acquired results, the proposed method has demonstrated its performance to track the GMPP through a series of extensive shading tests. Consequently, the scanning approach emerges as a compelling solution, offering dual outcomes, both facilitating the implementation of the reconfiguration technique and providing valuable insights into the type of anomalies encountered through the P_V curve analysis.

V. Conclusion

Ultimately, the proposed GMPPT approach proved to be exceptionally effective in optimizing the power output of PV systems under anomalous conditions. The proposed GMPPT approach was demonstrated through extensive simulation tests to properly track and maintain the maximum power by using an Arduino board. Furthermore, this research undertakes a novel approach to reevaluate traditional methodologies, such as P&O, incremental conductance, and fuzzy logic by effectively illustrating their application. In this context, the GMPPT technique unequivocally highlights its imperative role in reconfiguration procedures and, intriguingly, as a potential avenue for photovoltaic array fault detection and diagnosis methods.

Acknowledgment

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References

[1] A. Bjørn, S. M. Lloyd, M. Brander, and H. D. Matthews, "Renewable energy certificates threaten the integrity of corporate science-based targets," *Nature Climate Change*, vol. 12, no. 6, pp. 539–546, Jun. 2022, number: 6 Publisher: Nature Publishing Group. [Online]. Available: https://www.nature.com/articles/s41558-022-01379-5

[2] H. Oufettoul, N. Lamdihine, S. Motahhir, N. Lamrini, I. A. Abdelmoula, and G. Aniba, "Comparative Performance Analysis of PV Module Positions in a Solar PV Array Under Partial Shading Conditions," *IEEE Access*, vol. 11, pp. 12 176–12 194, 2023, conference Name: IEEE Access.

[3] C. Aoughlis, A. Belkaid, I. Colak, O. Guenounou, and M. A. Kacimi, "Automatic and Self Adaptive P&O MPPT Based PID Controller and PSO Algorithm," in *2021 10th International Conference on Renewable Energy Research and Application (ICRERA)*, Sep. 2021, pp. 385–390, iSSN: 2572-6013.

[4] A. Chalh, A. El Hammoumi, S. Motahhir, e. g. Abdelaziz, A. Derouich, M. Masud, and M. AlZain, "Investigation of Partial Shading Scenarios on a Photovoltaic Array's Characteristics," *Electronics*, Dec. 2021.

[5] H. Karmouni, M. Chouiekh, S. Motahhir, I. Dagal, H. Oufettoul, H. Qjidaa, and M. Sayyouri, "A Novel MPPT Algorithm based on Aquila Optimizer under PSC and Implementation using Raspberry," in *2022 11th International Conference on Renewable Energy Research and Application (ICRERA)*, Sep. 2022, pp. 446–451, iSSN: 2572-6013.

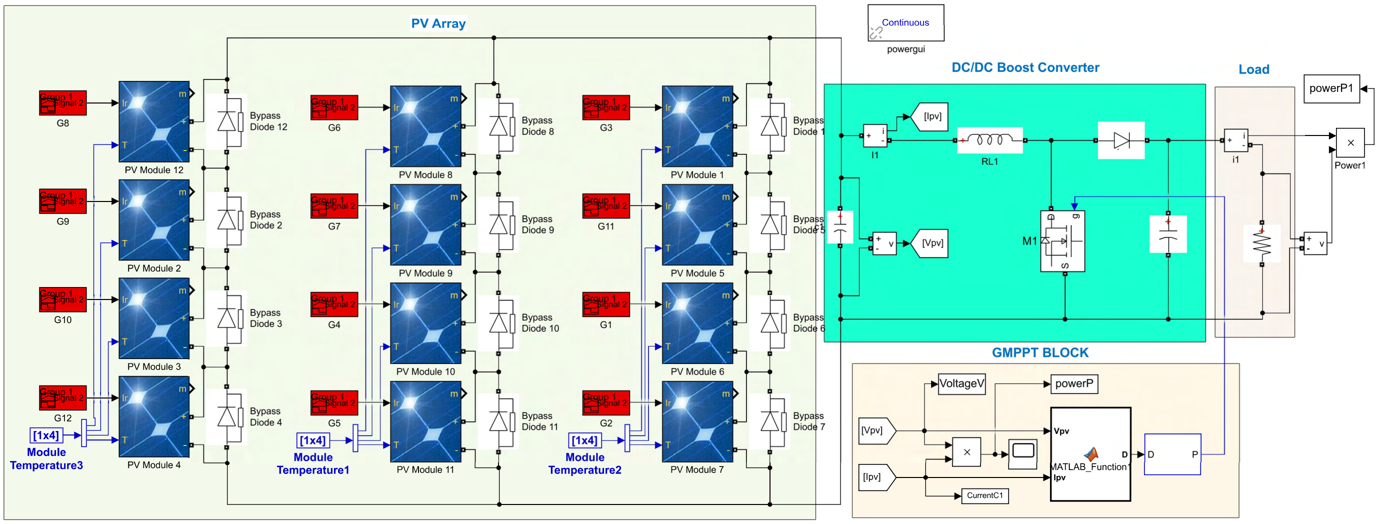

Fig. 7: Diagram of the proposed GMPPT approach on MATLAB software.

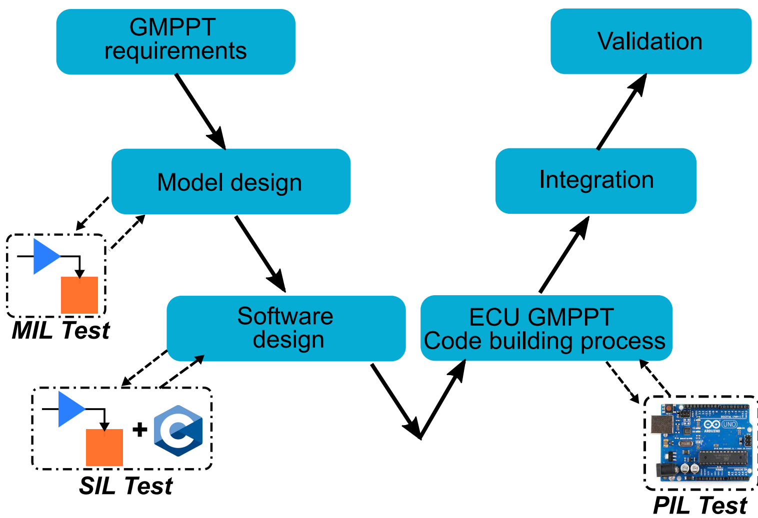

Fig. 8: MIL, SIL and PIL tests in the V-cycle development process.

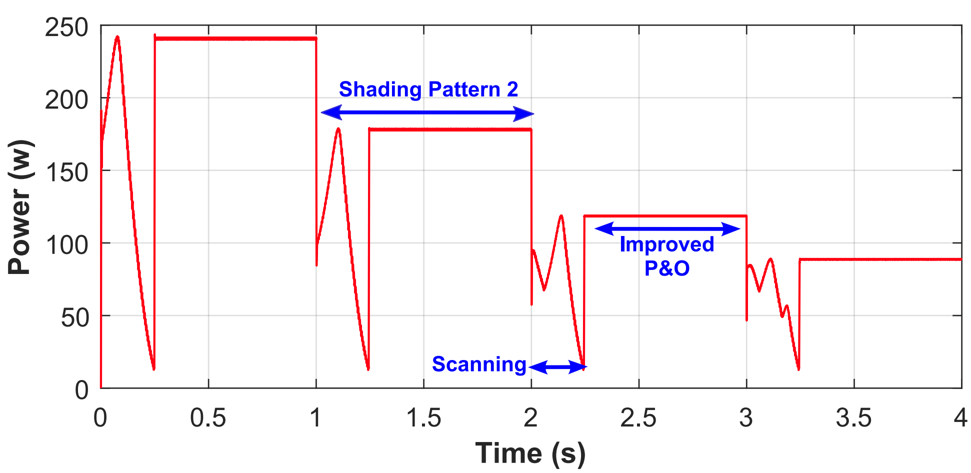

Fig. 9: Power produced by the PV array of the first partial shading cluster.

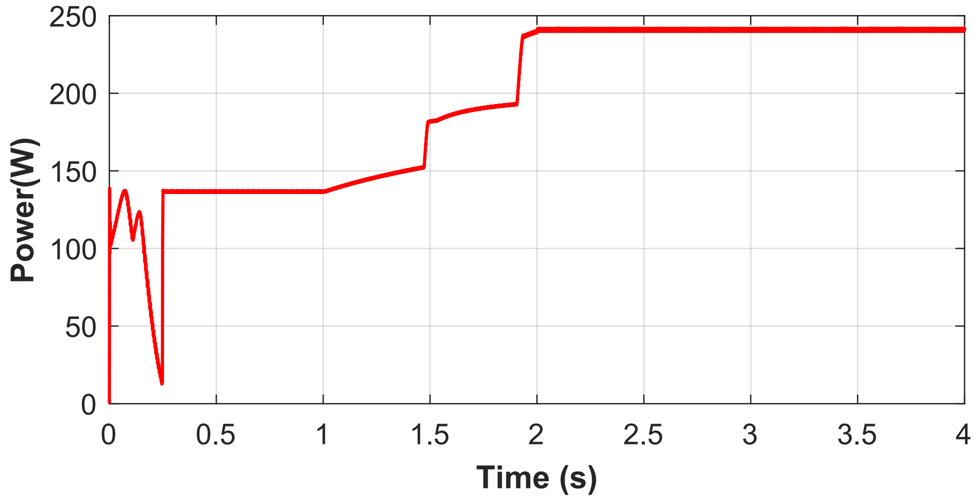

Fig. 10: Power generated by the second scenario of the second partial shading group.

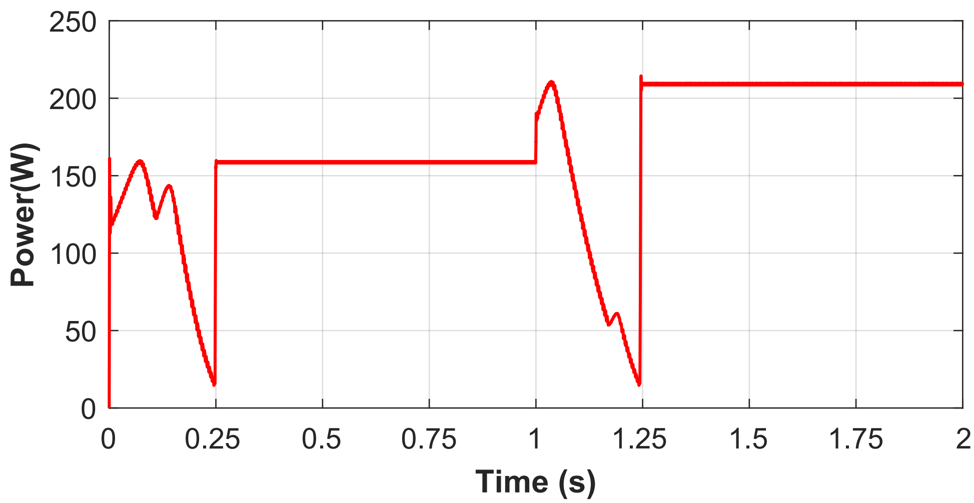

Fig. 11: Power generated by the first scenario of the second partial shading set.

[6] A. O. Baba, G. Liu, and X. Chen, "Classification and Evaluation Review of Maximum Power Point Tracking Methods," *Sustainable Futures*, vol. 2, p. 100020, Jan. 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2666188820300137

[7] S. Benhadouga, A. Belkaid, I. Colak, M. Meddad, and A. Eddiai, "Experimental Validation of The Sliding Mode Controller to Improve The Efficiency of The MPPT Solar System," in *2021 10th International Conference on Renewable Energy Research and Application (ICRERA)*, Sep. 2021, pp. 333–337, iSSN: 2572-6013.

[8] R. Z. Caglayan, K. Kayisli, N. Zhakiyev, A. Harrouz, and I. Colak, "A Review of Hybrid Renewable Energy Systems and MPPT Methods," *International Journal of Smart Grid - ijSmartGrid*, vol. 6, no. 3, pp. 72–78, Sep. 2022, number: 3. [Online]. Available: https://ijsmartgrid.ijrer.org/index.php/ijsmartgridnew/article/view/248

[9] H. Oufettoul, S. Motahhir, I. Ait abdelmoula, and G. Aniba, "Optimized topology for a photovoltaic array using switches control," *Energy Conversion and Management*, vol. 291, p. 117315, Sep. 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0196890423006611

[10] J. Solórzano and M. A. Egido, "Automatic fault diagnosis in PV systems with distributed MPPT," *Energy Conversion and Management*, vol. 76, pp. 925–934, Dec. 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S019689041300530X

[11] M. Muthuramalingam and P. S. Manoharan, "Comparative analysis of distributed MPPT controllers for partially shaded stand alone photovoltaic systems," *Energy Conversion and Management*, vol. 86, pp. 286–299, Oct. 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0196890414004555

[12] I. Abdelmoula, S. Elhamaoui, O. Elalani, A. Ghennioui, and M. Aroussi, "A photovoltaic power prediction approach enhanced by feature engineering and stacked machine learning model," *Energy Reports*, vol. 8, pp. 1288–1300, Nov. 2022.

[13] H. Oufettoul, S. Motahhir, G. Aniba, and I. Ait Abdelmoula, "Comprehensive Analysis of MPPT Control Approaches under Partial Shading Condition," in *2022 11th International Conference on Renewable Energy Research and Application (ICRERA)*, Sep. 2022, pp. 352–359, iSSN: 2572-6013.