Mehran University Research Journal of Engineering and Technology

https://doi.org/10.22581/muet1982.3147

2024, 43(3) 136-149

Optimization of MPPT perturb and observe algorithm for a standalone solar PV system

Muhammad Rehan, Muhammad Mateen Afzal Awan *

Department of Electrical Engineering, University of Management Technology, Sialkot – 51310 Punjab Pakistan

* Corresponding Author: Muhammad Mateen Afzal Awan, Email: mateen.afzal@skt.umt.edu.pk

Received: 11 January 2024, Accepted: 24 June 2024, Published: 01 July 2024

KEYWORDS

Solar Photovoltaic system

Maximum Power Point Tracking

P&O

Augmented Perturb and Observe

Uniform Weather Condition

ABSTRACT

Solar photovoltaic technology is dealing with the challenge of optimal power production from PV cells under all circumstances. This is possible by forcing the PV system to operate at maximum power point (MPP). Therefore, an algorithm is designed to take the operating power point towards MPP using an electronic circuit. The most used algorithm in the market is P&O due to its simple structure, easy implementation, and cheap circuitry. Whereas the weaknesses associated with P&O are steady state oscillations, PV array dependency, and slow tracking speed. We have put efforts into reducing the tracking time and removing the steady-state oscillations. After the detailed analysis, we have made some structural changes to get the required results. The proposed technique is named the optimized P&O (OP&O) algorithm. Both algorithms have been applied to the 90-watt PV system specifically designed for this purpose. The PV system with both algorithms is simulated in MATLAB/Simulink at different loads. The results have shown remarkable achievement in tracking speed, steady state oscillations, and ease of implementation.

1. Introduction

In contemporary energy systems, numerous challenges have emerged, including energy generation deficits, escalating energy demands, network stability concerns, greenhouse gas (GHG) emissions, and escalating costs [1]. Recent statistics [2, 3] have highlighted the rapid growth in energy demand across the residential, commercial, and industrial sectors, resulting in the depletion of fossil fuel resources, cost inflation, environmental degradation, and network overloads, leading to instability. Traditional power grid models typically address energy shortages by adding fossil fuel-based power generation plants and expanding transmission and distribution network capacities. However, such measures entail substantial capital investment, increased maintenance costs, and energy networks. Larger networks have become progressively more challenging to accomplish, susceptible to security threats, including cyberattacks, and prone to operational faults. Moreover, in conventional grids, large energy generation plants (fossil fuel-based or renewable) are usually connected remotely from load centers. Under such conditions, unpredictable weather-related disruptions to large renewable energy sources concentrated in specific areas can destabilize the entire system. To mitigate potential system instability, fossil fuel-based spinning reserves must be maintained, resulting in high costs and environmental concerns. Consequently, realizing the full potential of renewable energy to alleviate network overloads, GHG emissions, surging energy demands, soaring costs, and system vulnerabilities is constrained within the confines of the conventional grid.

Renewable DGs within smart distribution systems operate in two primary modes: 1) Grid-connected mode, where DGs supply customer-owned loads and export surplus power to the national grid, and 2) Standalone mode, where DGs provide power to isolated communities in situations where connecting to the national grid is either challenging or financially infeasible [6].

Standalone Solar PV system is an ideal application in remote rural areas and scenarios [7] where alternative power sources are unavailable for meeting lighting, appliances, and other energy needs. [6, 8].

Renewable energy sources encompass numerous forms such as wind, solar, hydrobiofuel, biomass tidal wave, and geothermal [9-15]. Among these, solar energy is the most abundant natural resource on Earth [16]. A PV system, also recognized as a solar power system or solar energy system, is a technique that changes sunlight into electrical energy. PV is one of the renewable sources that is widely used nowadays to cope with energy crises. PV is simple technology, user-friendly, less computation, and easy implementation. According to the report of the International Energy Agency Worldwide, energy utilization increased by 44% from 2006 to 2030. [17, 18]. It is renowned for its reliability, environmental friendliness, pollution-free operation, low maintenance requirements, and ease of installation in residential, commercial, parking, and vehicle parking settings [19-21]. A PV cell typically has a lifespan of 25-30 years and a payback period of approximately three years [22].

The MPP tracking (MPPT) is regarded as the simplest, most cost-effective, and most effective means of enhancing the efficiency of PV systems. It requires minimal investment and can

- Reduce Overall PV System Costs
- Increase Electricity Generation
- Reduce The Physical Footprint of PV Systems
- Shorten The Payback Period
- Improved Grid Stability

MPPT algorithms can be considered into two groups: I) conventional algorithms, which employ incremental scanning methods to identify the MPP based on the (P-V) curve of an array, without exploring the entire curve. These algorithms are less appropriate for global MPPT (GMPPT) under partial shading environments. [27-29], and II) soft-computing algorithms that utilize randomization concepts to address nonlinear problems, such as GMPPT under PSCs [30].

In light of these considerations, this paper introduces an optimized P&O MPPT algorithm called Optimized P&O (OP&O). The proposed algorithm successfully removed the steady-state oscillation, enhanced the MPP, and tracking speed, and achieved an efficient output.The evaluation Performance of MPPT algorithms is based on well-defined benchmarks sourced from the existing literature [31-33], including the following:

- Tracking speed
- Structural complexity
- Computational complexity
- Efficiency
- Array dependence
- Oscillation

A solar PV cell, constructed primarily from silicon, represents a ground-breaking semiconductor device that effectively captures solar light and converts it into electricity through the principles of the photoelectric effect. This transformative process converts incoming electromagnetic radiation into a reliable electric current. When interconnected ingeniously, these individual PV cells combine to form larger and more potent entities known as PV modules and PV arrays [23-26]. The specific arrangement of these PV cells within the modules and arrays is intricately designed to meet the required output specifications, optimizing the efficiency of this ingenious energy conversion process.

Tracking speed measures how quickly an algorithm reaches the MPP to save time, while structural complexity gauges the implementation challenges, and computational complexity relates to the tracking speed and implementation difficulties. Steady-state oscillations indicate the stability of the power output, whereas array dependence affects the tracking speed.

2. Literature Review

2.1 Conventional MPPT Algorithms

Traditional algorithms are known for their ease of implementation and simple widely used in situations characterized by UWC. These algorithms have demonstrated notable effectiveness in such weather conditions. The conventional MPPT algorithm functions by continuously comparing the latest (n) results with the previous (n-1) results at each step.

The array of conventional MPPT algorithms includes the following.

- P&O [34-46]
- Incremental Conductance [47-56]
- Hill Climbing [57-59]
- Fractional Short Circuit Current [60-62]
- Fractional Open Circuit Voltage [63-65]

2.1.1 P&O algorithm

The P&O algorithm is the extensively adopted conventional MPPT algorithm in the market, as documented in reference [36].

It accomplishes MPP tracking by perturbing a single variable, typically the voltage. Its popularity arises from its cost-effectiveness and straightforward implementation, which are attributed to its simplistic structure. However, a noteworthy drawback is that persistent steady-state oscillations are encountered around the MPP. Furthermore, it faces challenges in accurately tracking the Global MPP (GMPP) under PSC.

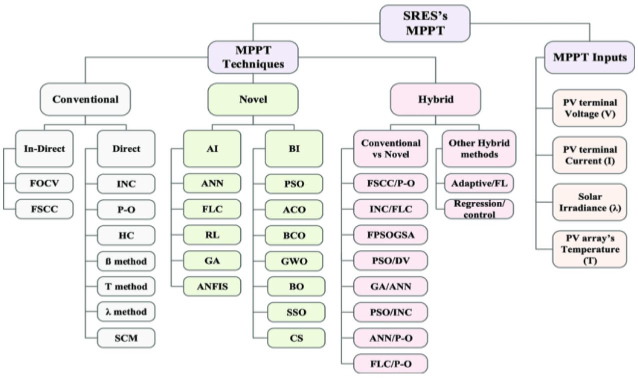


Fig. 1. Important MPPT Algorithms Techniques for Solar PV System [34-36]

A refinement of the P&O algorithm, leveraging variable step sizes, has been introduced in references [31, 36, 43, 67, 68]. Initially, it operates with a larger step size, progressively reducing the step size as it approaches MPP. This enhancement accelerates the tracking process but does not eliminate the oscillation issue.

For better results, the Delta P&O technique, as described in [35], substitutes a set step size for the traditional perturbation step size. The perturbation step size is currently optimized to improve the performance.

As a significant advancement, researchers introduced a hybrid of the P&O algorithm with Fuzzy Logic Control (FLC) algorithms [38]. Oscillations are mitigated by incorporating changes in the error (D) into the algorithm, which is calculated using a fuzzy rule table.

According to research in [37], there is an inverse relationship between a PV module's efficiency and disturbance. A new method for effectively lowering steady-state oscillations is proposed, which involves a perturbation rate with a constant duty ratio.

Another innovative approach, detailed in [43], introduced boundary conditions for temperature and power variables. The MPPT controller generates duty cycles based on the data, leading to an effective oscillation reduction.

Furthermore, oscillations were effectively eliminated in reference [69] through the introduction of a clever condition within the P&O algorithm termed "decrease and fix." When oscillations commence, the step size progressively decreases with each perturbation, until it reaches zero. Additionally, it monitors changes in currents and voltages to detect weather variations.

It is vital to note that while the P&O algorithm, along with its improved iterations, exhibits remarkable success under UWC, it encounters limitations under Partial Shading Environmental Conditions.

2.1.2 Hill climbing

The Hill Climbing (HC) algorithm employs a methodology comparable to the P&O algorithm, with the primary distinction residing in the choice of perturbing variables. In the HC algorithm, duty cycle (D) is a parameter subjected to perturbation.

The HC algorithm systematically adjusts the duty cycle (D) and monitors the resulting changes in the PV array power output. When the power change was positive, it persisted with perturbations in a similar direction. Equally, if the change is negative(-Ve), the algorithm backs the track of perturbation. Oscillations can manifest when the MPP is reached, as elucidated in references [57-59].

An endeavor to enhance the tracking precision of the HC algorithm was undertaken in reference [57], employing an interleaved boost converter. Notable success was achieved under circumstances characterized by a steady change in illumination.

In a subsequent advancement, a novel approach involving a Digital Signal Processor (DSP) controller was harnessed to construct a hardware prototype, subjecting it to testing across various illumination conditions, as described in [58]. This endeavor yielded a remarkable 17.5% betterment in the convergence speed.

A comparable approach was applied in reference [59] to investigate the suitability of the HC algorithm for grid-connected systems, drawing a comparison with the P&O algorithm.

It is important to highlight that the HC algorithm while offering its advantages, is susceptible to oscillations around the MPP and faces limitations in tracking the global MPP (GMPP) under PSC.

2.1.3 Incremental conductance algorithm

The Incremental Conductance (InC) algorithm shares the fundamental concept with the P&O algorithm but employs different criteria for perturbation. Initially, it initiates changes in a variable, primarily the voltage, after recording the values of "P" (power), "V" (voltage), and current. It calculates the ratio of the change in power (ΔP) to that in voltage (ΔV). If this ratio is positive, the voltage is continuously adjusted in a similar direction; otherwise, the perturbation direction is reversed. This process continues until the ratio of ΔP to ΔV equals zero, indicating the attainment of the MPP.

An enhancement was introduced in reference [48] by incorporating a variable step change in voltage to augment the tracking speed.

Furthermore, an alternative approach involving the utilization of a flyback converter was explored in reference [50]. The variable frequency constant duty and constant frequency variable duty were experimented with and produced effective results for a standalone PV system [51].

A hybrid of Fuzzy Logic Control and InC algorithm was tested in [53], using a Cuk converter. This hybridization led to improvements in the response time and a reduction in errors. Moreover, this hybrid approach was also employed in subsequent studies using a boost converter in [54] and a Single-Ended Primary Inductor Converter in [52].

It is noteworthy that the Incremental Conductance (InC) algorithm is well suited for low-power applications and demonstrates remarkable efficacy when confronted with gradual changes in illumination, as highlighted in references [54, 55]. However, the challenge of steady-state oscillations remains unresolved, as noted in previous studies [53, 54].

2.1.4 Fractional short circuit current algorithm

The fractional short-circuit (FSC) algorithm, also known as the short-current pulse MPPT method [61, 70-73], adopts a straightforward approach that relies on the short-circuit current (Isc) of the PV array. This algorithm strategically employs a concise and direct path to maximize the power output. Researchers have observed that under UWC, the current at the MPP, denoted as IMPP, consistently amounts to approximately 90% of the Isc of the PV system. Consequently, a scaling factor is introduced, whose value must remain below one, thereby allowing the IMPP to serve as a reference for the controller to precisely locate the MPP [74].

The FSC algorithm is particularly suitable for applications characterized by high voltages and low currents. However, this has not garnered extensive research attention, resulting in limited scholarly contributions. Notable among these is the assertion of 90% MPPT efficiency for the FSC algorithm when applied to solar PV systems [75, 76].

An intelligent iteration of the FSC algorithm was presented in [75], introducing upper and lower current limits to facilitate the measurement of a new value for Isc. Moreover, an advancement in the FSC algorithm performance was achieved by incorporating a lookup table [77]. This approach computes the error and reduces it using a PI controller. Notably, a comparative analysis was not conducted in this study.

It is essential to emphasize that the FSC MPPT algorithm is specifically tailored for UWC and is not suitable for addressing the challenges posed by PSC.

2.1.5 Fractional open circuit voltage

The Fractional Open Circuit (FOC) algorithm represents a straightforward, yet effective approach employed for MPPT [78-80]. This algorithm adopts a concise and direct methodology by leveraging the open-circuit voltage (Voc) of the PV system. Researchers have empirically determined that under UWC, the voltage at the MPP, denoted as VMPP, consistently equates to approximately 76% of the Voc of the corresponding PV system. Consequently, an adjustable factor is introduced, the value of which must remain below one. This factor allows the VMPP to serve as a reference for the controller to accurately pinpoint the MPP [84].

Notably, the research contributions in this field are somewhat limited. To effectively scale the implementation of the FOC algorithm, an initial measurement of Voc must be conducted under unloaded conditions for the PV system [Reference 81].

One notable enhancement introduced to the FOC algorithm is the concept of a switched semi-pilot cell, as detailed in [82]. This innovative addition not only augmented the accuracy of the conventional FOC MPPT algorithm but also resulted in tangible reductions in power losses.

The FOC algorithm has also been employed judiciously in hybrid configurations with other MPPT algorithms, yielding improved results.

It is imperative to emphasize that the FOC MPPT algorithm has been specially designed for operation under UWC and is not suited to address the challenges posed by PSC.

2.1.6 Performance analysis of conventional MPPT algorithms

After conducting an in-depth literature review of conventional MPPT algorithms, we have concluded that despite having the strengths of simple structure, easy implementation, and cheap circuitry requirement, the conventional algorithms possess the weaknesses of slow tracking speed, steady state oscillations, dependency on the size of PV system, and bad performance under PSC. Yet an excellent choice for solar PV systems under UWC.

The rest of this paper is organized as follows: In Section 2, we discuss the P&O algorithm in Section 3, the proposed model is discussed, the results and simulation are discussed in Section 4, in Section 5, the conclusion is presented, and in Section 6, the reference list is provided.

Table 1

Performance evaluation of conventional MPPT algorithms

Evaluation Parameter	P&O	HC	INC	FSCC	FOCV
Oscillations	Average	Average	Reduce	Zero	Zero
Memory	Low	Low	Low	Low	Low
Global MPP Capability	Absent	Absent	Absent	Absent	Absent
Structural Complexity	No	No	Limited	No	No
Execute Time	High	High	High	High	High

3. P&O Algorithm

In solar PV systems, the P&O MPPT algorithm is a widely used approach that maximizes power generation and system efficiency. Its major goal is to locate and maintain the MPP or operating point where the PV system produces the most feasible power output. The P&O MPPT algorithm operates as follows.

a) Initial Operating Point:

The algorithm starts with an initial operating point where the PV system is operating. This point can be anywhere on the voltage-current, (V-I) curve of the PV panel.

b) Perturbation:

The algorithm perturbs (changes) the functioning current of voltages slightly and detects the resulting variation in power output. It can increase or decrease the voltage and current by a predetermined step size, often referred to as the perturbation step.

c). Power Measurement:

After perturbation, the algorithm checks the power output of the PV panel at the new operational point. This is usually done by multiplying the measured voltage and current values.

d) Comparison:

The algorithm comparations the power output at the new operating point with the previous one.

a. If the power output has increased, the algorithm continues to perturb in the same direction (i.e., either increase voltage or current) because it is moving closer to the MPP.
b. If the power output has declined, the algorithm changes the perturbation direction (i.e., if it increases voltage, it now decreases voltage, and vice versa).

e) Iteration:

Steps 3 and 4 are repeated at regular intervals. The algorithm keeps perturbing and observing the power output until it reaches a point where further perturbing results in a power reduction. This indicates that the algorithm has reached the MPP.

f) Tracking:

Once the MPP is touched, the algorithm incessantly tracks the operating point to ensure that it stays at the MPP, as environmental conditions and the PV panel's characteristics may change over time.

Advantages of the P&O MPPT algorithm:

- Simple structure
- Easy to implement.
- Cost-effective implementation

Disadvantages of the P&O MPPT algorithm:

- Steady-state oscillations:
- PV array dependent
- Slow tracking speed
- Fail under PSC

The solution to overcome some or all the mentioned weaknesses is the ultimate purpose.

4. Proposed Optimized P&O MPPT Algorithm

The proposed optimized P&O MPPT algorithm is designed by introducing some structural modifications in the conventional P&O. Instead of involving multiple checks before deciding selecting the direction of perturbation, we have exempted the check of voltage/current and connect the decision variable directly to the duty cycle. Based on the observation of change in power we direct the duty cycle to move in a specific direction with different step sizes. Starting with the large stepsize to get closer to the MPP as early as possible just by observing the change in power and reducing the duty cycle as get closer to the MPP. The continuous decrease will reduce the duty cycle to a negligible value that stabilizes the output, gets the real MPP, and obtains zero steady-state oscillations.

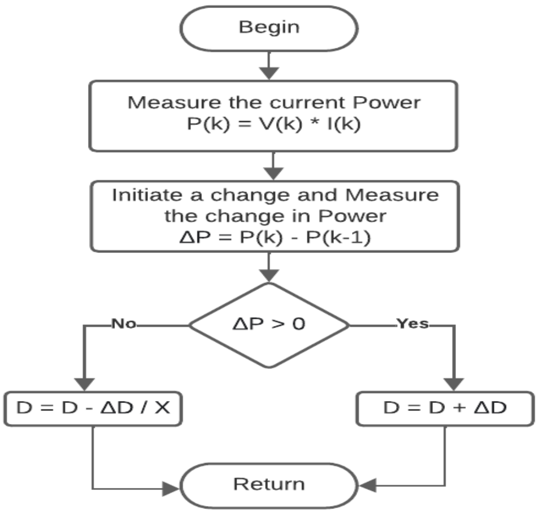


Fig 2. Flowchart Of the Proposed OP&O MPPT Algorithm

4.1 Testing Scenarios for MPPT Algorithms

The simulated model of an off grid/standalone solar PV system is presented in Fig. 3. It is composed of a PV array, DC/DC boost converter, MPPT controller, embedded algorithm, and a DC load. The MPPT algorithm does not depend on the load [83]. We have implemented the proposed MPP algorithm using different loads to observe this claim.

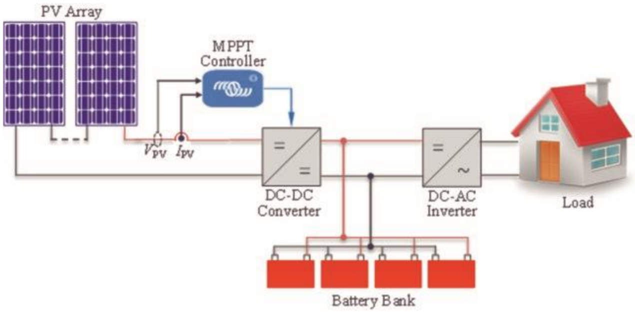


Fig. 3. Standalone Solar PV System [84]

4.2 Results and Discussion

A 90 Watts solar PV system of is designed and simulated in MATLAB/Simulink. The conventional and the proposed MPPT algorithms are tested and evaluated on the designed system. The power-voltage (P-V) characteristic curve for the 90-watt PV system is presented in Fig. 4.

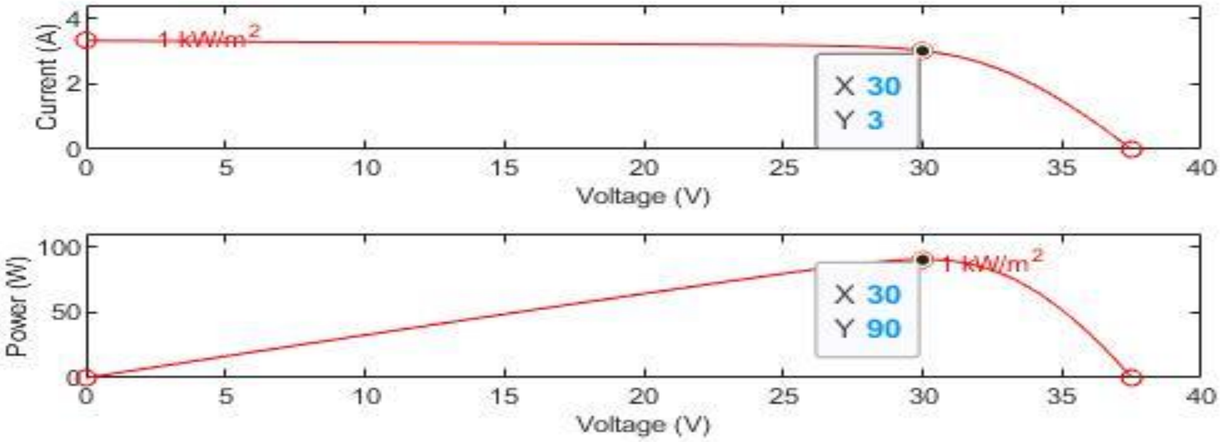
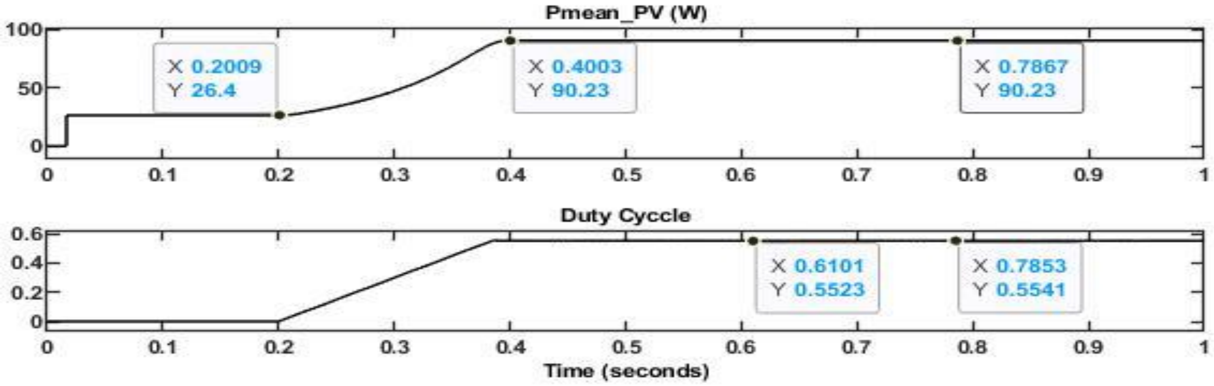


Fig. 4. Power-Voltage Characteristic Curve of 90-Watt PV System

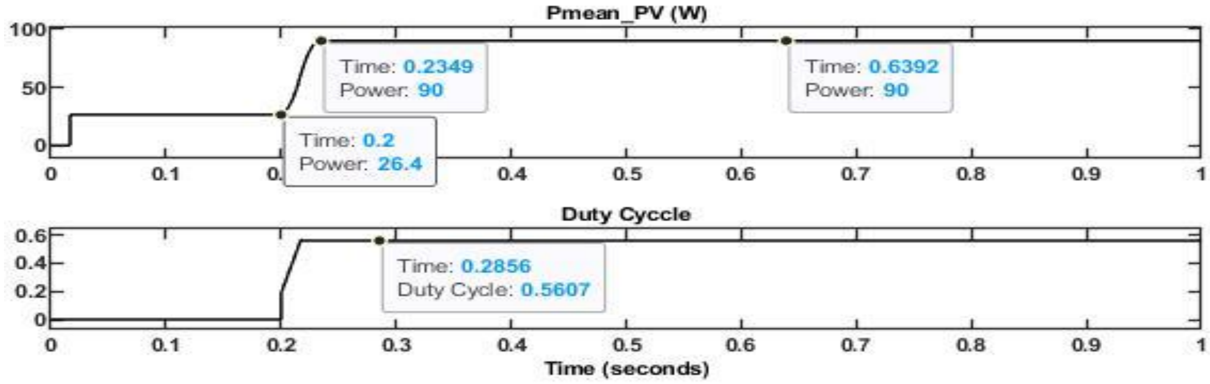
The P-V characteristic curve in Fig. 4 depicts that under non-shading and at standard test conditions (1000W/m2, and 25oC) the PV system produces 90-watt, at 30-volts and 3-amperes at its MPP. Considering this standard value, the extracted output of both the conventional P&O and the proposed optimized P&O will be evaluated. However, the MPPT tracking speed comparison will be relative to each other.

Initially, we applied the P&O algorithm to the designed 90-watt solar PV system that tracked the MPP and extracted 90-watt output in 0.2-sec with an efficiency of 100%. The oscillations are very small and negligible. We repeat the same conventional P&O algorithm with a large step size and notice a sufficient improvement in MPPT speed but the steady state oscillations get bigger due to the large step size of the duty cycle. The oscillations noticed in the power and duty cycle are 0.01-watt and 0.036D respectively. However, the MPPT time reduces to 0.04-sec. The improvement in tracking speed is good but at the cost of steady-state oscillations, that assures no stable output.

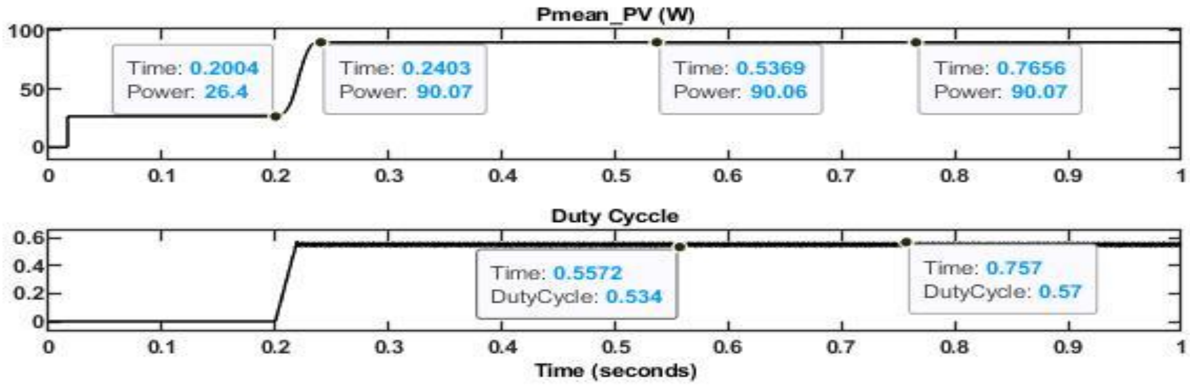
At the application of the proposed OP&O MPPT algorithm, we have found remarkable findings of zero steady-state oscillations at large step size (the reason and logic are explained in the section-3.3). The proposed OP&O algorithm attained a 90-watt power output with 100% efficiency in just 0.03-sec without steady-state oscillations. These achievements of the proposed OP&O MPPT algorithm against the conventional P&O algorithm are visually explained in Fig. 5 and are summarized in Table 2.



a) Conventional (P&O) Algorithm with A Small Step Size



b) Conventional (P&O) Algorithm with Large Step Size



c) Optimized (P&O) Large Step Size

Fig. 5. Results of the P&O and OP&O Algorithms at Standard Test Conditions

Table 2

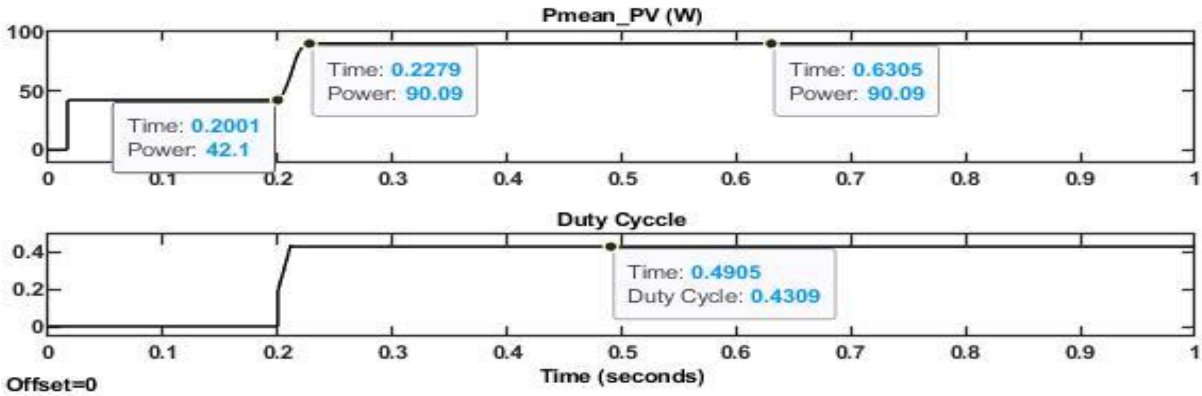
Performance summary of P&O and OP&O algorithms at standard test conditions

Case	Algorithms	Rated Power	Extracted Power (W)	Efficiency (%)	Tracking Speed (Sec)	Improvement in Tracking Speed
1	P&O (Small Step Size)	90	90	100	0.2	
2	P&O (Large Step Size)	90	Variable	NA	0.04	85%
3	Optimized P&O	90	90	100	0.03	

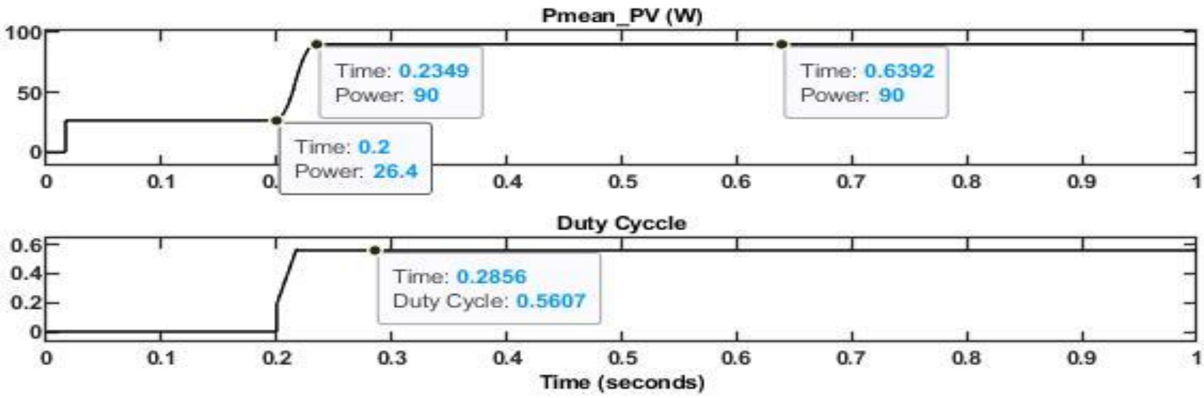
As claimed in the description, the proposed OP&O MPPT algorithm attains its target and outperforms the conventional P&O MPPT algorithm in terms of efficiency, MPPT tracking speed, and steady-state oscillations.

The 85% improvement in MPP tracking speed is a great achievement of the proposed OP&O algorithm. Solving the problems of utilizing small and large duty cycles precisely is the main task achieved that results in the remarkable improvement in MPPT speed.

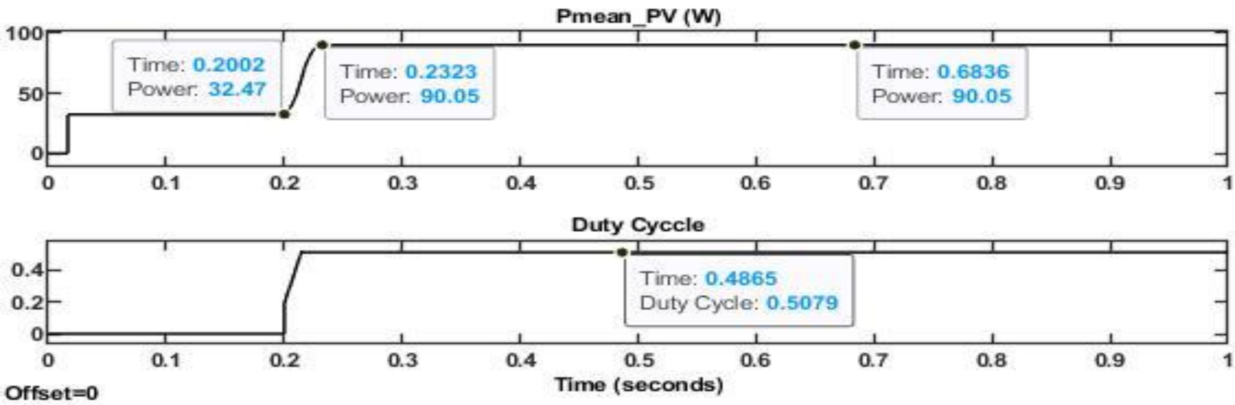
However, to further evaluate the Improvement of the proposed OP&O MPPT algorithm, the designed PV system is operated with different loads. Stable and efficient output at a variety of loads for the same PV system verifies the tracking capabilities of the proposed OP&O MPPT algorithm. The results of the proposed OP&O MPPT algorithm for the three different loads of 30-ohm, 40-ohm, and 50-ohm are presented in the Fig. 6. The proposed OP&O MPPT algorithm has successfully retained its performance and extracted the maximum possible output power from the solar PV system with various loads connected to the output, by incessantly operating the solar PV system at its MPP



a) Performance of The Proposed OP&O Algorithm at 30-ohm Load



b) Performance of The Proposed OP&O Algorithm at 40-ohm Load



c) Performance Evaluation of The Proposed OP&O Algorithm at 50 Ohms Load

Fig. 6. Performance Evaluation of the Proposed OP&O Algorithm at Various Loads

The summary of the MPPT ability of the proposed OP&O MPPT algorithm with various loads is summarized in Table 2.

The table describes the quality of tracking by the suggested OP&O algorithm. The achievement of MPP with 100% efficiency at a variety of loads in just 0.03 seconds without the steady state oscillations is the remarkable achievement of OP&O. Not only it has overcome the drawbacks of the conventional P&O algorithm but also strengthened the image of P&O in the market.

Table 3

Performance summary of the proposed OP&O algorithms at various loads

Load	Rated Power	Extracted power	Efficiency (%)	Tracking Speed (Sec)	Steady State Oscillation
30	90	90	100	0.03	Nil
40	90	90	100	0.03	Nil
50	90	90	100	0.03	Nil

Moreover, the capability of the proposed OP&O MPPT algorithm to detect the change in weather conditions to stop or resume its operation is tested. For this purpose, the change in solar illumination/irradiation is introduced twice in a row to check if the proposed OP&O MPPT algorithm can detect and restart the tracking process or not. The results demonstrated that the proposed OP&O MPPT algorithm has successfully stopped tracking after attaining the goal (MPP) and restarted the tracking process, each time it detects the change in solar illumination/irradiation. The results for this illumination-changing activity are presented in Fig. 8 Before that, a P-V characteristic curve of the solar PV system for the changed position of the solar illumination/irradiation is generated as shown in Fig. 7 and compared for the results.

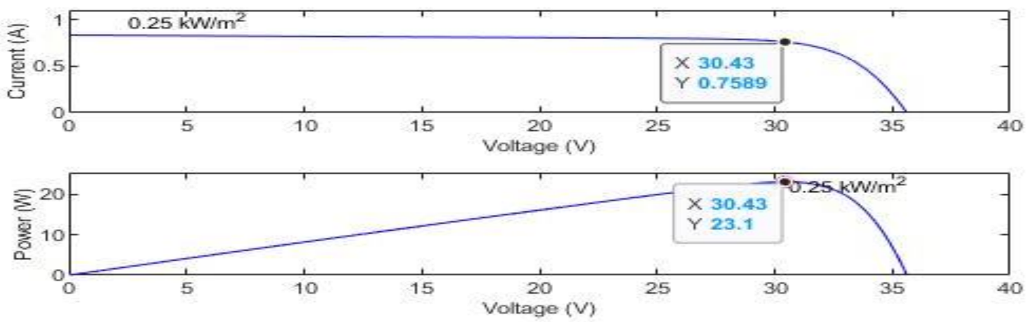


Fig. 7. Power-Voltage Characteristic Curve of a 90-Watt PV System For 250W/m2 Illumination

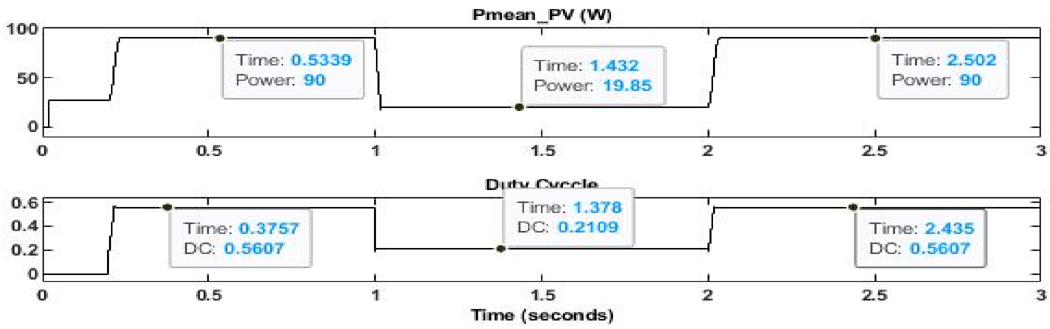


Fig. 8. Performance Evaluation of The Proposed OP&O Algorithm for Changing Weather Condition

The performance evaluation of the proposed OP&O MPPT algorithm for the changing weather conditions is presented in Fig. 8.

5. Future Work

Future work in this field should focus on the integration of P&O with emerging technologies to maximize its potential for advancing renewable energy generation and adaptive control strategies.

6. Conclusion

The paper introduced and demonstrated the significant potential of the OP&O algorithm as a revolutionary approach to MPPT in PV systems. Both the conventional P&O and the proposed OP&O MPPT algorithms are applied to the designed 90-watt solar PV system. The performance evaluation is conducted on the benchmarks of steady-state oscillations, MPPT speed, and design simplicity. Further, simulations are repeated for different loads to evaluate the performance of both algorithms. The results have shown that the proposed OP&O algorithm has outperformed the conventional P&O algorithm in tracking speed, and structural simplicity and achieved zero steady-state oscillations.

7. References

[1] A. Raza and T. N. Malik, "Energy management in commercial building microgrids", Journal of Renewable and Sustainable Energy, vol. 11, no. 1, p. 015502, 2019.

[2] M. M. A. Awan, “Ordering technique for the MPPT of an islanded solar PV system”, Sustainability, vol. 15, no. 4, pp. 3332, 2023

[3] M. Nasir and M. F. Zia, "Global MPPT algorithm for PV systems under partial shading conditions", 2014 16th International Power Electronics and Motion Control Conference and Exposition, 21-24 Sept. 2014, pp. 667-672.

[4] M. A. Judge, A. Khan, A. Manzoor, H. A. Khattak, “Overview of smart grid implementation: Frameworks, impact, performance and challenges”, Elsevier. Journal of Energy Storage, vol. 1, no. 49, pp. 104056, 2022.

[5] R. H. Lasseter, "Smart distribution: Coupled microgrids", Proceedings of the IEEE, vol. 99, no. 6, pp. 1074-1082, 2011.

[6] N. Hashim, “DC-DC boost converter design for fast and accurate MPPT algorithms in stand-alone PV system”, International Journal of Power Electronics and Drive Systems, vol. 9, no. 3, pp. 1038, 2018.

[7] M. M. A. Awan, M. Y. Javed, A. B. Asghar, and K. Ejsmont, “Economic integration of renewable and conventional power sources-A case study”, Energies, vol. 15, no. 6, pp. 2141, Mar. 2022.

[8] H. A. Sher, Qureshi, S.A., Paracha, Z.J., Kalam, A. and Owais, M., "Economical analysis of a 4KW stand-alone solar PV based system for rural electrification in Pakistan", 3rd International Engineering and Optimization Conference PEOCO2009 - Distributed Generation, Shah Alam, Selangor, Malaysia, 2009.

[9] A. Hassan, O. Bass, Y. M. Al-Abdeli, M. Masek, “A novel approach for optimal sizing of stand-alone solar PV systems with power quality considerations”, Elsevier. International Journal of Electrical Power and Energy Systems, vol. 1, no. 144, pp. 108597, 2023.

[10] W. Strielkowski, W, “Renewable energy in the sustainable development of electrical power sector”, A review. Energies, vol. 14, no. 24, pp. 8240, 2021.

[11] M. Khan and M. Iqbal, "Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland", Renewable energy, vol. 30, no. 6, pp. 835-854, 2005.

[12] S. N. Mishra and J. Lowitzsch, "Consumer (Co-) ownership in renewables in India", Energy Transition: Springer, 2019, pp. 587-610.

[13] R. Ahmad, A. F. Murtaza, and H. A. Sher, “Power tracking techniques for efficient operation of PV array in solar applications–A review”, Renewable and Sustainable Energy Reviews, vol. 1, no. 101, pp. 82-102, 2019

[14] E. T. Sayed, A. G. Olabi, A. H. Alami, A. Radwan, A. Mdallal, “Renewable energy and energy storage systems”, Energies, vol. 16, no. 3, pp. 1415, Feb. 2023.

[15] R. Yang, Y. Chen, and C. Xia, "Analysis of frequency oscillation caused by AGC control in yunnan power grid", 2018 International Conference on Power System Technology (POWERCON), 6-8 Nov. 2018 2018, pp. 441-446.

[16] M. M. A. Awan, and M. J. Awan, “Adapted flower pollination algorithm for a standalone solar photovoltaic system”, Mehran University Research Journal of Engineering & Technology, vol. 41, no. 4, pp.118-127, 2022.

[17] M. M. A. Awan, and T. Mahmood, “Modified flower pollination algorithm for an Offgrid solar photovoltaic system”, Mehran University Research Journal of Engineering & Technology, vol. 41, no. 4, pp. 95-105, 2022

[18] L. Baur and M. Uriona M, "Diffusion of PV technology in Germany: A sustainable success or an illusion driven by guaranteed feed-in tariffs? ", Energy, vol. 150, pp. 289-298, 2018/05/01/ 2018.

[19] A. Allouhi, S. Rehman, M. S. Buker, and Z. Said, "Up-to-date literature review on Solar PV systems: Technology progress, market status and R&D", Journal of Cleaner Production, vol. 202, 2022.

[20] V. Sharma and S. Chandel, "Performance and degradation analysis for long-term reliability of solar PV systems: A review", Renewable and Sustainable Energy Reviews, vol. 27, pp. 753-767, 2013.

[21] R. M. Moharil and P. S. Kulkarni, "Reliability analysis of solar PV system using hourly mean solar radiation data", Solar Energy, vol. 84, no. 4, pp. 691-702, 2010.

[22] C. Bankier and S. Gale, "Energy payback of roof mounted PV cells", ed, 2006.

[23] V. V. Tyagi, N. A. A. Rahim, N. A. Rahim, and J. A. L. Selvaraj, "Progress in solar PV technology: Research and achievement", Renewable and Sustainable Energy Reviews, vol. 20, pp. 443-461, 2013/04/01/ 2013.

[24] A. M. Shaikh, “Comparative analysis of different MPPT techniques using boost converter for PV systems under dynamic shading conditions”, Sustainable Energy Technologies and Assessments, vol. 1, no. 57, pp. 103259, 2023.

[25] M. Das, M. Pal, and V. Agarwal, "Novel high gain, high-efficiency DC-DC converter suitable for solar PV module integration with three-phase grid tied inverters", IEEE Journal of PVs, vol. 9, no. 2, pp. 528-537, 2019.

[26] Kebbab, L. Sabah, H. Nouri, “A comparative analysis of MPPT techniques for grid connected PVsFZ”, Technology & Applied Science Research, vol. 12, no. 2, pp. 8228-8235, 2022.

[27] M. M. A. Awan, and T. Mahmood, “Optimization of maximum power point tracking flower pollination algorithm for a standalone solar photovoltaic system”, Mehran University Research Journal Of Engineering & Technology, vol. 39, no. 2, pp. 267-278, Apr. 2020

[28] M. C. Di Piazza and G. Vitale, "PV field emulation including dynamic and partial shadow conditions", Applied Energy, vol. 87, no. 3, pp. 814-823, 2018.

[29] J. Ahmed and Z. Salam, "An MPPT for PV system using Cuckoo Search with partial shading capability", Applied Energy, vol. 119, pp. 118-130, 2014/04/15/ 2014.

[30] M. M. A. Awan, “A technical review of MPPT algorithms for solar photovoltaic system: SWOT analysis of MPPT algorithms”, Sir Syed University Research Journal of Engineering & Technology, vol. 12, no. 1, pp. 98-106, 2022

[31] M. M. A. Awan, and T. Mahmood, “A novel ten check maximum power point tracking algorithm for a standalone solar photovoltaic system”, Electronics, vol. 7, no. 11, pp. 327, Nov. 2018.

[32] S. Ahmed, S. Mekhilef, M. B. Mubin, and K. S. Tey, "Performances of the adaptive conventional MPPT algorithms for solar PV systems", Technologies and Assessments, vol. 1, no. 53, pp. 102390, Oct. 2022.

[33] M. M. A. Awan, M. Y. Javed, A. B. Asghar, and K. Ejsmont, “Performance optimization of a ten check MPPT algorithm for an offgrid solar photovoltaic system”, Energies, vol. 15, no. 6, pp. 2104, Mar. 2022.

[35] A. Pandey, N. Dasgupta, and A. K. Mukherjee, "High-performance algorithms for drift avoidance and fast tracking in solar MPPT system", IEEE Transactions on Energy Conversion, vol. 23, no. 2, pp. 681-689, 2008.

[36] A. K. Abdelsalam, A. M. Massoud, S. Ahmed, and P. N. Enjeti, "High-performance adaptive P&O MPPT technique for PV-based microgrids", IEEE Transactions on Power Electronics, vol. 26, no. 4, pp. 1010-1021, 2018.

[37] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, "Assessment of P&O MPPT algorithm implementation techniques for PV pumping applications", IEEE Transactions on Sustainable Energy, vol. 3, no. 1, pp. 21-33, 2012.

[38] M. A. A. M. Zainuri, M. A. M. Radzi, A. C. Soh, and N. A. Rahim, "Development of adaptive P&O-fuzzy control MPPT for PV boost dc-dc converter", IET Renewable Power Generation, vol. 8, no. 2, pp. 183-194, 2014.

[39] M. A. G. De Brito, L. Galotto, L. P. Sampaio, G. d. A. e Melo, and C. A. Canesin, "Evaluation of the main MPPT techniques for PV applications", IEEE Transactions on Industrial Electronics, vol. 60, no. 3, pp. 1156-1167, 2013.

[40] S. H. S. Ahmadi, M. Karami, M. Gholami, “Improving MPPT performance in PV systems based on integrating the incremental conductance and particle swarm optimization methods”, Springer. Transaction of Electrical Engineering. Iranian Journal of Science and Technology, vol. 1, no. 46, pp. 27-39, Oct. 2021.

[41] S. K. Kollimalla and M. K. Mishra, "A novel adaptive P&O MPPT algorithm considering sudden changes in the irradiance", IEEE Transactions on Energy Conversion, vol. 29, no. 3, pp. 602-610, 2014.

[42] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, "Operating characteristics of the P&O algorithm at high perturbation frequencies for standalone PV systems", IEEE Transactions on Energy Conversion, vol. 30, no. 1, pp. 189-198, 2017.

[43] M. H. Ibrahim, S. P. Ang, M. N. Dani, M. I. Rahman, “Optimizing step-size of perturb & observe and incremental conductance MPPT techniques using pso for grid-tied PV system”, IEEE Access, vol. 6, no. 11, pp. 13079-90, Feb. 2023.

[44] R. Raedani and M. Hanif, "Design, testing and comparison of P&O, IC and VSSIR MPPT techniques", 2014 International Conference on Renewable Energy Research and Application (ICRERA), 19-22 Oct. 2014 2014, pp. 322-330.

[45] G. Kanagachidambaresan, R. Anand, and A. Kalam, "P&O (InC) based MPPT controller for PV connected brushless DC motor drive", 2017 IEEE International Conference on Electrical, Instrumentation and Communication Engineering (ICEICE), 2017: IEEE, pp. 1-5.

[46] M. Y. Javed, A. F. Murtaza, Q. Ling, S. Qamar, M. M. Gulzar, "A novel MPPT design using generalized pattern search for partial shading", Energy and Buildings, vol. 1, no. 133, pp. 59-69, Dec. 2016.

[47] J. H. Lee, H. Bae, and B. H. Cho, "Advanced incremental conductance MPPT algorithm with a variable step size", s2006 12th International Power Electronics and Motion Control Conference, 30 Aug.-1 Sept. 2006 2006, pp. 603-607.

[48] G. Yuksek, A. N. Mete, “A P&O based variable step size mppt algorithm for PV applications”, Gazi University Journal of Science, vol. 36, no. 2, pp. 608-622, 2023

[49] L. Jiyong and W. Honghua, "A novel stand-alone PV generation system based on variable step size INC MPPT and SVPWM control", s 2009 IEEE 6th International Power Electronics and Motion Control Conference, 17-20 May 2019, pp. 2155-2160.

[50] A. Safari and S. Mekhilef, "Simulation and hardware implementation of incremental conductance MPPT with direct control method using cuk converter", IEEE Transactions on Industrial Electronics, vol. 58, no. 4, pp. 1154-1161, 2011.

[51] G. Hsieh, H. Hsieh, C. Tsai, and C. Wang, "PV power-increment-aided incremental-conductance MPPT with two-phased tracking", IEEE Transactions on Power Electronics, vol. 28, no. 6, pp. 2895-2911, 2013.

[52] T. njum, J. K. Nayak, and A. Ghosh, “A comparative analysis between perturb & observe and incremental conductance techniques for MPPT in PV system”, IEEE Power India International Conference, 2022, pp. 1-6.

[53] T. Radjai, L. Rahmani, S. Mekhilef, and J. P. Gaubert, "Implementation of a modified incremental conductance MPPT algorithm with direct control based on a fuzzy duty cycle change estimator using dSPACE", Solar Energy, vol. 110, pp. 325-337, 2014/12/01/ 2014.

[54] P. Sivakumar, A. Abdul Kader, Y. Kaliavaradhan, and M. Arutchelvi, "Analysis and enhancement of PV efficiency with incremental conductance MPPT technique under non-linear loading conditions", Renewable Energy, vol. 81, pp. 543-550, 2015/09/01/ 2015.

[55] U. M. C. Rao, B. M. V. Krishna, A. S. Babu, S. Suman, "Design and simulation of PV system with incremental conductance method for MPPT”, International Journal of Scientific Engineering and Technology, vol. 3, no. 5, pp. 643-646, May 2014.

[56] F. Mahmood, "Improving the PV modeling powerfactory", ed, 2012.

[57] M. Veerachary, T. Senjyu, and K. Uezato, "MPPT control of IDB converter supplied PV system", IEEE Proceedings - Electric Power Applications, vol. 148, no. 6, pp. 494-502, 2001.

[58] M. M. A. Awan, A. U. Khan, M. U. Siddiqui, H. Karim, and M. Bux, “Optimized hill climbing algorithm for an islanded solar photovoltaic system”, Mehran University Research Journal of Engineering & Technology, vol. 42, no. 2, pp.124-132, Apr. 2023.

[59] L. Fangrui, K. Yong, Z. Yu, and D. Shanxu, "Comparison of P&O and hill climbing MPPT methods for grid-connected PV converter", 2008 3rd IEEE Conference on Industrial Electronics and Applications, 3-5 June 2008 2008, pp. 804-807.

[60] M. Ramachandran, S. Chinnasamy, “A review on hill climbing optimization methodology”, Recent Trends in Management and Commerce, vol. 3, no. 1, pp. 1-7, 2022.

[61] A. M. A. Malkawi, A. Odat, A. Bashaireh, “A novel PV MPPT based on solar irradiance and circuit parameters estimation”, MDPI. Sustainability, vol. 14, no. 13, pp. 7699, Jun. 2022.

[62] N. Hyeong-Ju, L. Dong-Yun, and H. Dong-Seok, "An improved MPPT converter with current compensation method for small, scaled PV-applications", IEEE 2002 28th Annual Conference of the Industrial Electronics Society. IECON 02, 5-8 Nov. 2002 2002, vol. 2, pp. 1113-1118 vol.2.

[63] A. K. Sharma, R. K. Pachauri, “An investigation of various MPPT techniques applied to solar PV systems,” Computer Science, Technology and Applications, USA, 2022, pp. 65-90.

[64] J. H. R. Enslin, M. S. Wolf, D. B. Snyman, and W. Swiegers, "Integrated PV MPPT converter", IEEE Transactions on Industrial Electronics, vol. 44, no. 6, pp. 769-773, 1997.

[65] K. Kobayashi, H. Matsuo, and Y. Sekine, "A novel optimum operating point tracker of the solar cell power supply system", 2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551), 20-25 June 2004, vol. 3, pp. 2147-2151 Vol.3.

[66] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, "Assessment of P&O MPPT algorithm implementation techniques for PV pumping applications", IEEE Transactions on sustainable energy, vol. 3, no. 1, pp. 21-33, 2015.

[67] M. M. A. Awan, “Strategic perturb and observe algorithm for partial shading conditions: SP&O algorithm for PSC”, Sir Syed University Research Journal of Engineering & Technology, vol. 12, no. 2, pp. 26-32, Dec. 2022.

[68] J. D. Bastidas-Rodriguez, G. Spagnuolo, E. Franco, C. A. Ramos-Paja, and G. Petrone, "MPPT architectures for PV systems in mismatching conditions: a review", IET Power Electronics, vol. 7, no. 6, pp. 1396-1413, 2014, doi: 10.1049/it-pel.2013.0406.

[69] M. M. A. Awan and F. G. Awan, "Improvement of MPPT P&O algorithm for a standalone solar PV system", Mehran University Research Journal of Engineering and Technology, vol. 36, no. 3, pp. 501-510, 2017-07-01 2017.

[70] S. Alghuwainem, "Matching of a DC motor to a PV generator using a step-up converter with a current-locked loop", IEEE Transactions on Energy Conversion, vol. 9, no. 1, pp. 192-198, 1994.

[71] N. Mutoh, T. Matuo, K. Okada, and M. Sakai, "Prediction-data-based maximum-power-point-tracking method for PV power generation systems", 2002 IEEE 33rd Annual IEEE Power Electronics Specialists Conference. Proceedings (Cat. No. 02CH37289), 2018, vol. 3: IEEE, pp. 1489-1494.

[72] M. A. Masoum, H. Dehbonei, and E. F. Fuchs, "Theoretical and experimental analyses of PV systems with voltage and current-based maximum power-point tracking", IEEE Transactions on energy conversion, vol. 17, no. 4, pp. 514-522, 2002.

[73] Y. A. Puttalingaiah, A. G. Shesadri, “A cost-effective and optimized maximum PowerPoint tracking system for the PV model”, International Journal of Electrical and Computer Engineering, vol. 13, no. 5, pp. 4942-4949, Oct. 2023.

[74] A. R. Reisi, M. H. Moradi, and S. Jamasb, "Classification and comparison of MPPT techniques for PV system: A review", Renewable and sustainable energy reviews, vol. 19, pp. 433-443, 2013.

[75] H. A. Sher, A. F. Murtaza, A. Noman, K. E. Addoweesh, K. Al-Haddad, and M. Chiaberge, "A new sensor less hybrid MPPT algorithm based on fractional short-circuit current measurement and InC MPPT", IEEE Transactions on Sustainable Energy, vol. 6, no. 4, pp. 1426-1434, 2015.

[76] R. Faranda and S. Leva, "Energy comparison of MPPT techniques for PV System,", WSEAS transactions on power systems, vol. 3, no. 6, pp. 446-455, 2008.

[77] J. Ghaisari, M. Habibi, and A. Bakhshai, "An MPPT controller design for PV systems based on the optimal voltage factor tracking", 2017 IEEE Canada Electrical Power Conference, 2007: IEEE, pp. 359-362.

[78] J. Schoeman and J. Van Wyk, "A simplified maximal power controller for terrestrial PV panel arrays", 1982 IEEE Power Electronics Specialists Conference, 1982: IEEE, pp. 361-367.

[79] M. A. El Ela and J. Roger, "Optimization of the function of a PV array using a feedback control system", Solar cells, vol. 13, no. 2, pp. 107-119, 1984.

[80] X. Wang, Z. Zheng, M. Aillerie, "Cooperative control of online impedance spectroscopy monitoring method and MPPT method for PV panels", IEEE. 24th European Conference on Power Electronic and Applications, 2022, pp. 1-10.

[81] J. H. Enslin, M. S. Wolf, D. B. Snyman, and W. Swiegers, "Integrated PV MPPT converter", IEEE Transactions on Industrial Electronics, vol. 44, no. 6, pp. 769-773, 2017.

[82] D. Baimel, S. Tapuchi, Y. Levron, and J. Belikov, "Improved fractional open circuit voltage MPPT methods for PV systems", Electronics, vol. 8, no. 3, p. 321, 2019.

[83] A. Mellit, H. Rezzouk, A. Messai, and B. Medjahed, "FPGA-based real-time implementation of MPPT-controller for PV systems," Renewable Energy, vol. 36, no. 5, pp. 1652-1661, 2011/05/01/ 2011.

[84] S. Obukhov, A. Ibrahim, A. A. Z. Diab, A. S. Al-Sumaiti, and R. Aboelsaud, "Optimal performance of dynamic particle swarm optimization based maximum power trackers for stand-alone PV system under partial shading conditions", IEEE Access, vol. 13, no. 8, pp.20770-20785, 2020.