# Enhancing PV System Efficiency: An Analysis of Intelligent MPPT Algorithms

**K. Arutselvan[1], P. N. Palanisamy[2], M. Sugumaran[3], T. Manikumar[4]**

*[1]R P Sarathy Institute of Technology, Salem, Tamilnadu, India.*
*[2]Mahendra College of Engineering, Salem, Tamilnadu, India.*
*[3]Sona College of Technology, Salem, Tamilnadu, India.*
*[4]Kalasalingam Academy of Research and Education, (Deemed to be University), Krishnan Kovil, Tamilnadu, India.*

The efficiency of photovoltaic (PV) systems is highly dependent on their ability to operate at the Maximum Power Point (MPP) under varying environmental conditions. Traditional Maximum Power Point Tracking (MPPT) algorithms, such as Perturb and Observe (P&O) and Incremental Conductance, often fall short in rapidly changing irradiance and temperature scenarios. This work explores the implementation of intelligent MPPT algorithms using Metaheuristic Optimization Methods, to improve tracking efficiency, response time and overall system performance. Specifically, the analysis focuses on the adaptability and robustness of these algorithms in handling the nonlinear characteristics of PV systems. Simulation results and performance comparisons demonstrate the potential of these algorithms to enhance the overall energy yield of PV systems, particularly in dynamic environments.

**Keywords:** PSO; GWO; CS; PV; P&O and FSSO.

## 1. Introduction

Fossil fuel-powered plants inflict irreversible harm on the environment by emitting pollutants into the air. Consequently, PV systems have emerged as a superior alternative to traditional energy sources. These systems comprises interconnected PV modules arranged either in series or parallel to achieve the desired power capacity. However, when overshadowed by large structures, solar panels may become more susceptible to partial shading, diminishing their efficiency.

During partial shading, the PV and power-current (PI) curves of solar PV modules exhibit numerous local peaks (LMPP) and a single global peak (GMPP). It becomes crucial to monitor these peaks in order to optimize performance. However, conventional tracking algorithms suffer a decrease in effectiveness under partial shading, reducing overall system efficiency.

Classic tracking techniques such as P&O, InC, Fuzzy Logic (FL) and Neural Networks (NN) have been developed to enhance solar system efficiency under uniform irradiance conditions. While effective in tracking MPP under regular sunlight with a single peak, these methods are inadequate for optimizing the global peak (GMPP) under partial shading conditions (PSC).

Various optimization algorithms, including GA, PSO etc., have been devised to trace the MPP of PV systems. These approaches are comparatively less intricate and have demonstrated efficacy in achieving global optima in shaded scenarios.

A hybrid PSO-SVR (Particle Swarm Optimization - Support Vector Regression) approach has been formulated to mitigate ripple content in output current and oscillations. This technique enhances MPP tracking performance by integrating PSO with SVR technology. Their findings indicate that the proposed PSO-SVR method surpasses traditional PSO methods [1].

An extensive study was conducted on diverse soft computing methodologies aimed at monitoring the MPP of PV) systems amidst PSC. Their investigation encompassed AI-driven approaches including NN and FL [2].

An upgraded P&O algorithm was devised to enhance the tracking speed and increasing power yield from PV conversion systems [3]. Meanwhile, a refined PSO was introduced to maximize output power from PV power plants, especially in shading conditions. This modification involved tailoring PSO parameters specific to the algorithm, thereby expediting exploration of optimal sites. Experimental validation of these approaches was conducted utilizing microcontrollers [4,16].

PSO methodology has been utilised to track the MPP of PV systems across varying irradiation levels. Their simulation results revealed that the PSO method outperformed the traditional P&O method, particularly in PSC, yielding higher power output [5].

The efficacy of MPP control through the development of an Artificial Neural Network (ANN) featuring a single neuron was proven by [6]. It enhanced the performance of the switching converter by integrating a direction control strategy employing an adaptive neuron. To mitigate the risk of converging to local optima, the fundamental parameters of the ANN were fine-tuned using an offline method.

A meta-heuristic techniques were utilised to simulate MPPT under PSC [7]. Similarly, an enhanced P&O technique for MPP tracking in PV systems has been developed [8].

A TLBO approach has been presented to extract global power output under PSC. The simulation findings demonstrated the TLBO's effectiveness in accurately determining the global MPP [9].

An hybrid MineBlast and TLBO has been proposed for extracting the global maximum power from PV systems [10].

A PSO with tailored coefficients, FFA also employed to monitor the global power output of a PV module under PSC [11, 12]. A hybrid approach combining the P&O with PSO has been proposed to mitigate continuous oscillations around the MPP [13].

A GA based topology has been presented to determine the optimal number of neurons necessary for training multi-layer neural networks, aiming to track maximum power [14]. An innovative differential evolution (DE) approach for extracting the overall power output in shaded scenarios under non-uniform irradiation conditions was formulated [15,17].

After reviewing various methodologies documented in the literature for tracking the MPP under PSC, it was observed that bio-inspired algorithms demonstrate superior tracking speed and accuracy. Consequently, the current research endeavors to explore different bio-inspired frameworks such as PSO, GWO, CS, and FSSO to ascertain the global MPP under diverse shading conditions.

PSC in PV System

Partial shading conditions occur in PV systems when some of the solar cells or panels are shaded while others remain exposed to sunlight. This shading can be caused by various factors such as nearby buildings, trees, clouds, or even dirt on the panels. Figure 1 depicts PV characteristics under both uniform irradiation and PSC condition.

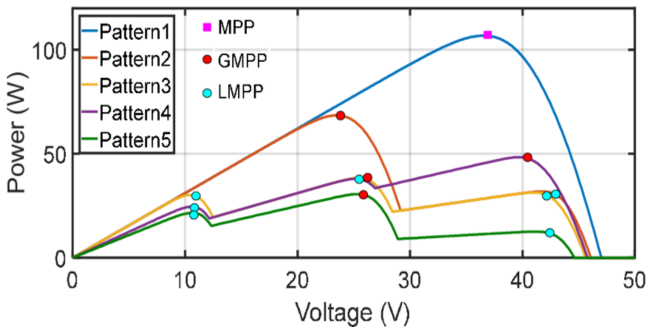


Figure 1 PV characteristics curve

Integrating a power converter between the PV and the load, regulates the internal resistance of the PV panels based on prevailing climatic conditions. This setup prompts the panels to operate close to their MPP. Consequently, numerous researchers have leveraged MPPT algorithms to adjust the duty cycle of a converter [5]. By modulating the switching duty cycle (D), the converter can flexibly vary its output voltage. If D=0, the converter's output voltage remains below its lowest point, while approaching unity, it results in the highest output voltage.

## 2. MPPT Topologies

This section summarizes the MPPT approaches investigated in this research, which are used to track the GMPP of a PV system under PSC.

PSO Algorithm

The PSO algorithm operates on principles derived from social-psychological theories, functioning as an optimization system. It adopts a one-population search approach where individual locations, termed "particles," are iteratively updated. This enables each particle to continuously monitor its position and fitness within the search space, facilitating the discovery of optimal solutions. Throughout the algorithm, particle velocity is adjusted iteratively to approximate both local and global optimal solutions. In each iteration, the acceleration parameters are randomly assigned, operating independently in every scenario [18].

Figure 2 illustrates the flowchart of the PSO MPPT approach.

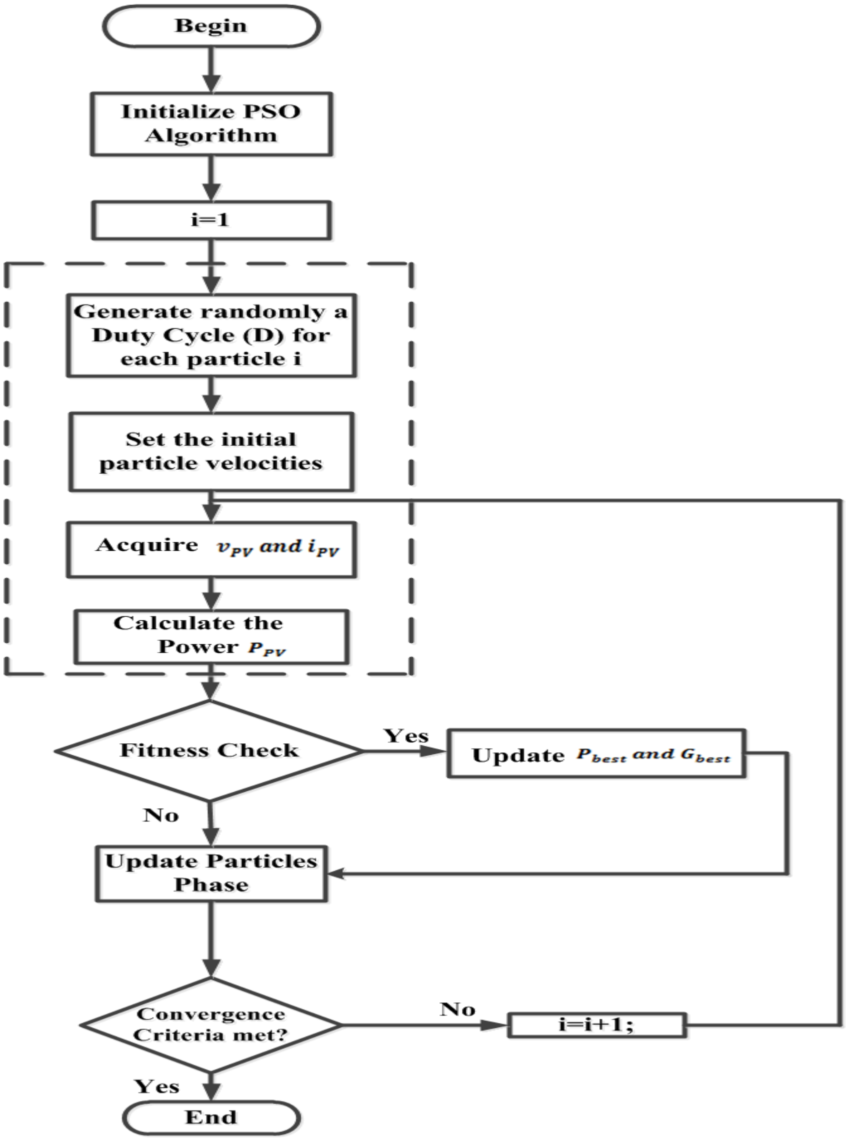


Figure 2 Flowchart of PSO based MPPT

Grey Wolf Optimization (GWO) Algorithm

The GWO is a bioinspired algorithm inspired by grey wolves' hunting behaviour. GWO models the leadership hierarchy within a wolf pack, categorizing wolves into four distinct roles: alpha, beta, delta, and omega. [19].

It has found wide utility in optimization process due to its fine characteristics such as,

(i) Initial search does not require derivation of information

(ii) Fast convergence of solution because of its global optimization in entire search space

Figure 3 represents the flowchart of GWO MPPT technique,

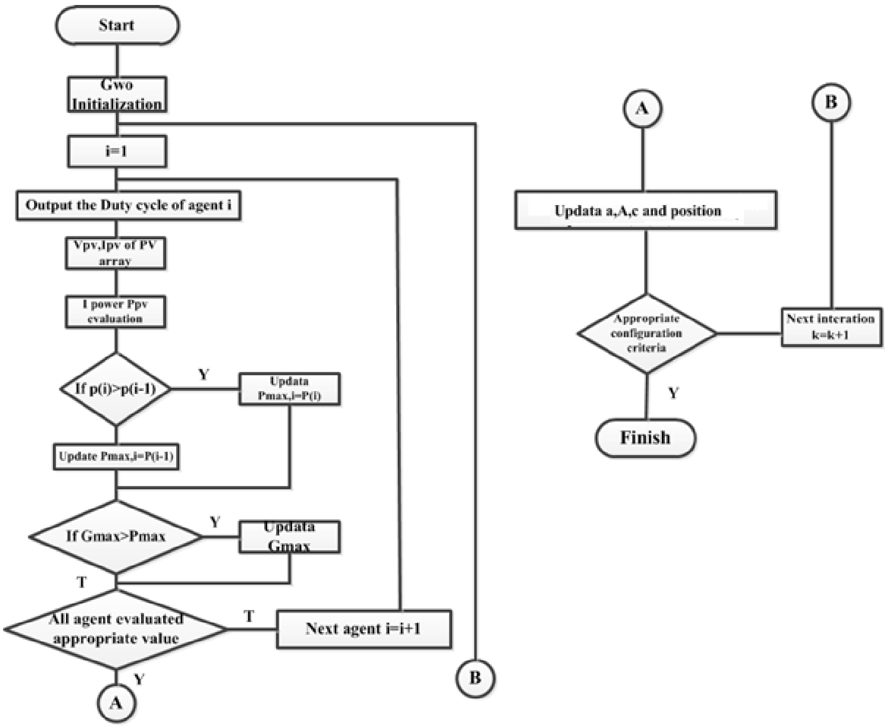


Figure 3 Flowchart of GWO - MPPT

Cuckoo search optimization (CS) algorithm

The CS algorithm is a nature-inspired optimization technique inspired by the brood parasitism of some cuckoo species. This algorithm has been applied to MPPT in PVsystems to enhance energy extraction efficiency. Levy flights are employed to update the duty cycle using the gamma function, as defined by equations (1) and (2).

$$\delta = \left[\frac{\gamma(\beta+1)\times \sin\pi\times\frac{\beta}{2}}{\gamma\left(\frac{\beta+1}{2}\right)\times\beta\times 2^{\frac{\phi-1}{2}}}\right]^{\frac{1}{\emptyset}} \qquad (1)$$

$$CP_i^{1+k} = CP_i^k + \alpha \times G_{best} \times \frac{|u|}{|v|^{\frac{1}{\emptyset}}} \qquad (2)$$

It primarily aims to determine the Gbest value of D. It generates a random value for D and stores it in a matrix. When the system demands power for the load, the algorithm is activated, discarding the poorest solutions and replacing them with new nests to enhance optimization [20].Fig. 4. depicts a flowchart for the CSA.

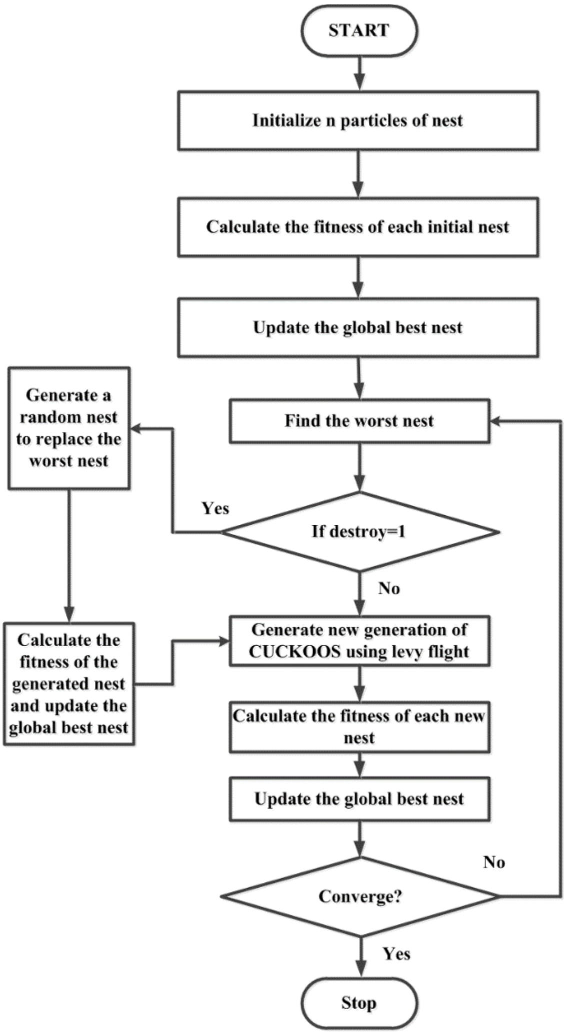


Figure 4 Flowchart of CS based MPPT

Flying Squirrel Search Optimization (FSSO) Algorithm

Based on the gliding behavior of squirrels, this algorithm was created. Instead of flying, they prefer an unusual mode of mobility known as "gliding," which is energy efficient and allows them to cover large distances quickly and effectively [21].

When executing the FSSO technique for MPPT, the following assumptions are considered:

- The duty ratio (D) of the converter is considered as the decision variable.

- The FSSO strategy is adapted by removing the presence of hunters to shorten the time required to reach the GMP.

## 3. Simulation Results

This section presents a comprehensive analysis of the algorithm's performance, evaluating its effectiveness in achieving the desired objectives. Through simulations, key metrics such as efficiency, accuracy, and convergence speed are assessed under various operating conditions. The results are compared against existing techniques to highlight improvements and identify potential challenges. A detailed discussion follows, providing insights into the behavior of the algorithm, the implications of the findings, and the overall impact on system performance. Table I depicts the parameters of the Boost DC-DC converter used in this work.

Table 1 Converter Specification

| Parameters | Values |
|---|---|
| Power | 1000W |
| Input Voltage Vin | 70-100 V |
| Output Voltage | 200V |
| Inductor L | 26mH |
| Capacitor C | 173µF |
| Load Resistance R | 40 |
| Switching Frequency | 10kHz |

The irradiation values for the shading pattern across each of the modules are approximately 1000 W/m², 300 W/m², and 600 W/m², respectively. Figure 5 illustrates the current-voltage (I-V) and power-voltage (P-V) characteristics of the PV strings under partial shading conditions.

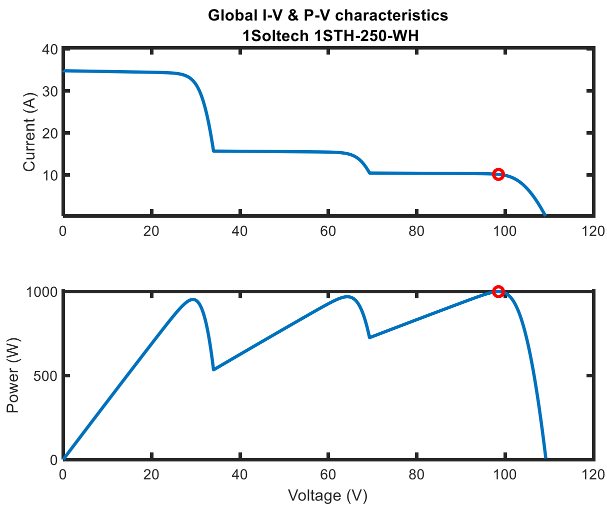


Figure 5 P-V and P-I curves under PSC

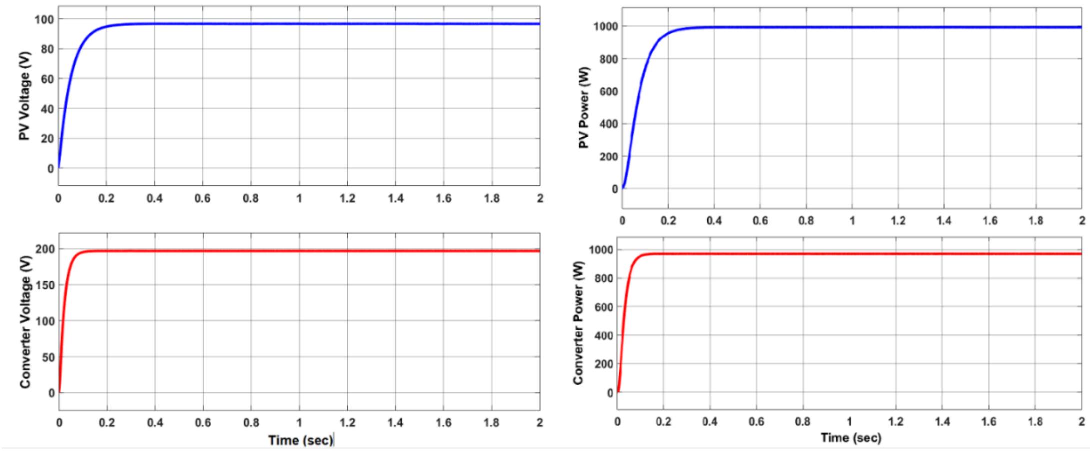


Figure 6a Simulation results - PSO

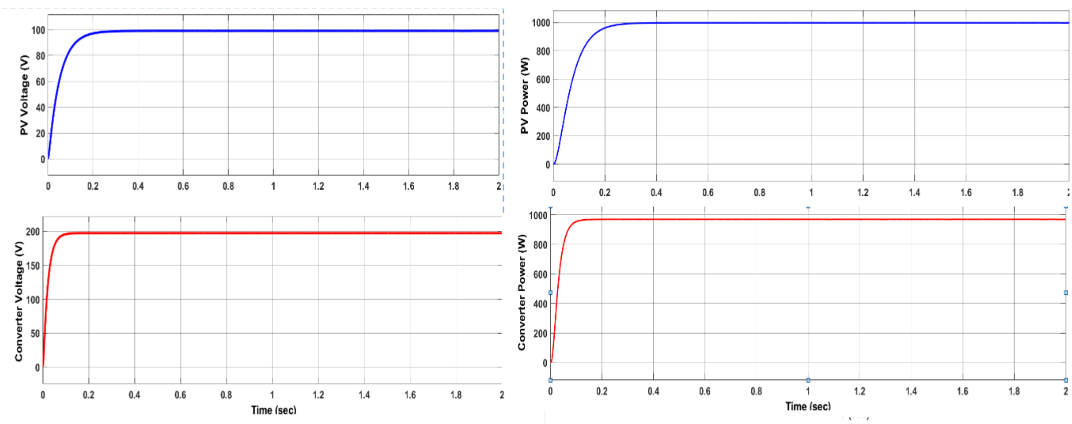


Figure 6b Simulation results - CS

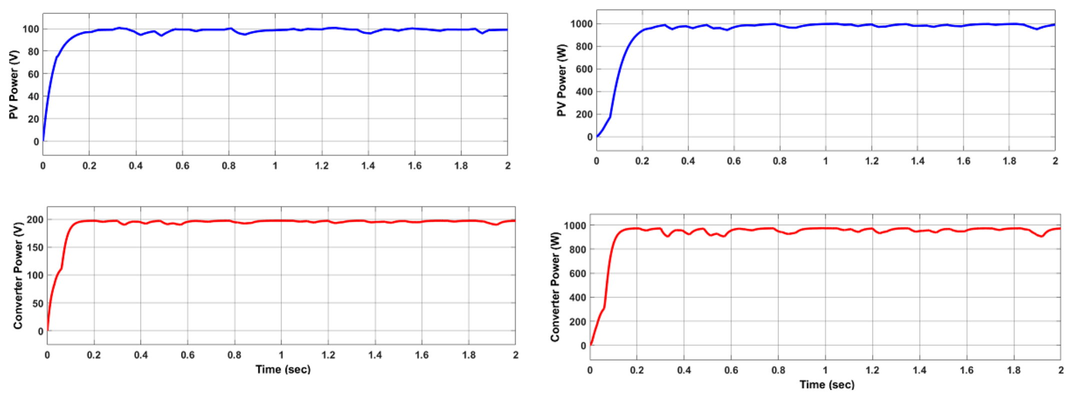


Figure 6c Simulation results - GWO

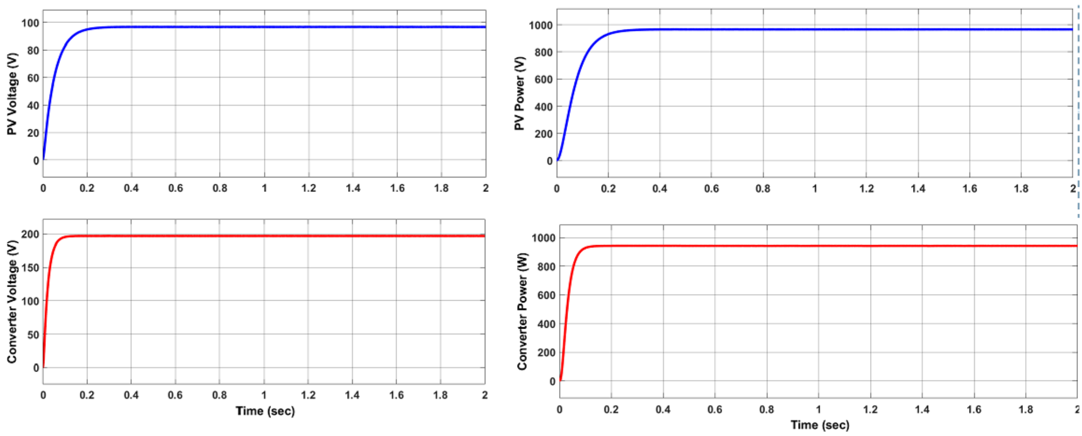


Figure 6d Simulation results - FSSO

From the above simulation results, it is observed that the conventional P&O algorithm fails to track the MPP under partial shading condition. The oscillations at the output of the PV system are high under P&O topology. So it is concluded that Conventional MPPT topology is not suitable for partial shading condition.

In case of GWO topology, even though the oscillation is less when compared P&O, but their exists. Hence, power remains unsteady under this topology. The output power of the PV module converges to the MPP with random oscillations.

While considering FSSO topology, the settling time is high when compared to PSO and CS. However, it suppresses the oscillation at the output.

Next to FSSO, CS and PSO exhibits better performance. However, PSO's average convergence time is longer when compared to that of CS.

Moreover, the CS algorithm demonstrates rapid convergence, attaining global optimal values within mere seconds. Additionally, it is noted that employing the CS algorithm yields higher output voltage and power from the PV module, while also achieving steady-state values more expeditiously compared to alternative algorithms.

Thus from all the above analysis, it is concluded that CS topology exhibits more capability of attaining global maximum power during various shading conditions with less time. Hence, CS exhibits superiority over all the topologies discussed in this work.

The statistical results obtained from this work is summarized in Table 2. It depicts the performance of all the MPPT topologies discussed in this work under partial shading condition with the simulation time period of 1s.

Table 2 Comparison Table

| Methods | Efficiency | Average tracking time (sec) |
|---|---|---|
| P& O | 770 | 0.204 |
| CS | 1000 | 0.140 |
| FSSO | 998 | 0.163 |
| GWO | 992 | 0.321 |
| PSO | 1000 | 0.156 |

The statistical analysis tabulated in table 2 depicts that CS tracks a both greater voltage and power from the PV module in comparison with the GWO, PSO, FSSO and P&O technique under different shading patterns.

## 4. Conclusion

This work aims to investigate and compare MPPT strategies based on bio inspired algorithms such as PSO, CS, FSSO and GWO. When tracking the maximum power point, these bio inspired MPPT techniques solve the issues of traditional MPPT strategies (P&O), even in the presence of rapid changes in irradiance and shadows on solar modules. The MPPT approaches investigated have shown to have good behaviour and performance. Also, from the analyzed results, it is proven that CS achieves rapid convergence. It can able to track global optima in less time and can help to increase maximum power extraction from solar system.

## References

1. Abokhalil, A. (2020). Maximum power point tracking for a PV system using tuned support vector regression by particle swarm optimization. Journal of Engineering Research, 8(4). https://doi.org/10.36909/jer.v8i4.9113.
2. Dileep, G., & Singh, S. N. (2017). Application of soft computing techniques for maximum power point tracking of SPV system. Solar Energy, 141, 182-202.. http://dx.doi.org/10.1016/j.solener.2016.11.034.
3. Özçelik, M. A., & Yilmaz, A. S. (2015). Improving the performance of MPPT in PV systems by modified Perturb-and-Observe algorithm. Journal of Engineering Research, 3, 1-20. http://dx.doi.org/10.7603/s40632-015-0024-5.
4. Chao, K. H., Lin, Y. S., & Lai, U. D. (2015). Improved particle swarm optimization for maximum power point tracking in photovoltaic module arrays. Applied energy, 158, 609-618. http://dx.doi.org/10.1016/j.apenergy.2015.08.047.
5. Nagadurga, T., Narasimham, P. V. R. L., & Vakula, V. S. (2021). Harness of maximum solar energy from solar PV strings using particle swarm optimisation technique. International Journal of Ambient Energy, 42(13), 1506-1515. https://doi.org/10.1080/01430750.2019.1611643.
6. Kofinas, P., Dounis, A. I., Papadakis, G., & Assimakopoulos, M. N. (2015). An Intelligent MPPT controller based on direct neural control for partially shaded PV system. Energy and Buildings, 90, 51-64. http://dx.doi.org/10.1016/j.enbuild.2014.12.055.
7. Ahmed, J., & Salam, Z. (2015). A critical evaluation on maximum power point tracking methods for partial shading in PV systems. Renewable and Sustainable Energy Reviews, 47, 933-953. DOI: 10.1016/j.rser.2015.03.080.
8. Dileep, G., & Singh, S. N. (2015). Maximum power point tracking of solar photovoltaic system using modified perturbation and observation method. Renewable and Sustainable Energy Reviews, 50, 109-129. http://dx.doi.org/10.1016/j.rser.2015.04.072.
9. Rezk, H., & Fathy, A. (2017). Simulation of global MPPT based on teaching–learning-based optimization technique for partially shaded PV system. Electrical engineering, 99, 847-859. https://link.springer.com/article/10.1007/s00202-016-0449-3.
10. Fathy, A., & Rezk, H. (2016). A novel methodology for simulating maximum power point trackers using mine blast optimization and teaching learning based optimization algorithms for partially shaded photovoltaic system. Journal of renewable and sustainable energy, 8(2). http://dx.doi.org/10.1063/1.4944971.
11. Phimmasone, V., Kondo, Y., Kamejima, T., & Miyatake, M. (2010, October). Evaluation of

extracted energy from PV with PSO-based MPPT against various types of solar irradiation changes. In 2010 International Conference on Electrical Machines and Systems (pp. 487-492). IEEE.

12. Sundareswaran, K., Peddapati, S., & Palani, S. (2014). MPPT of PV systems under partial shaded conditions through a colony of flashing fireflies. IEEE transactions on energy conversion, 29(2), 463-472. http://dx.doi.org/10.1109/TEC.2014.2298237.
13. Sundareswaran, K., & Palani, S. (2015). Application of a combined particle swarm optimization and perturb and observe method for MPPT in PV systems under partial shading conditions. Renewable Energy, 75, 308-317. http://dx.doi.org/10.1016/j.renene.2014.09.044.
14. Kulaksız, A. A., & Akkaya, R. (2012). A genetic algorithm optimized ANN-based MPPT algorithm for a stand-alone PV system with induction motor drive. Solar Energy, 86(9), 2366-2375. http://dx.doi.org/10.1016/j.solener.2012.05.006.
15. Tajuddin, M. F. N., Arif, M. S., Ayob, S. M., & Salam, Z. (2015). Perturbative methods for maximum power point tracking (MPPT) of photovoltaic (PV) systems: a review. International Journal of Energy Research, 39(9), 1153-1178. https://doi.org/10.1002/er.3289.
16. Renaudineau, H., Donatantonio, F., Fontchastagner, J., Petrone, G., Spagnuolo, G., Martin, J. P., & Pierfederici, S. (2014). A PSO-based global MPPT technique for distributed PV power generation. IEEE Transactions on Industrial Electronics, 62(2), 1047-1058. http://dx.doi.org/10.1109/TIE.2014.2336600.
17. Sankara Subramanian, A.T. and Senthil Kumar, M., 2023. Hybrid optimization technique-based maximum power point tracking for single-stage grid-connected PV systems. Clean Technologies and Environmental Policy, 25(9), pp.2999-3025. http://dx.doi.org/10.1007/s10098-023-02542-y.
18. Rajakumar, P., Senthil Kumar, M., Sakthidasan, A., Sundar, R., Pasupulati, B. and Amosedinakaran, S., 2023, August. Performance of Fuzzy MPPT for a Distributed Photovoltaic System Under Changing Environmental Condition. In International Conference on Electrical and Electronics Engineering (pp. 201-218). Singapore: Springer Nature Singapore. http://dx.doi.org/10.1007/978-981-99-8289-9_16.
19. Nagarathinam, E., Devaraju, B., Jayamoorthy, K., Radhakrishnan, P., ChandraMohan, S.L., Perumal, V. and Balakrishnan, K., 2024. Maximizing Solar Potential Using the Differential Grey Wolf Algorithm for PV System Optimization. Energy Engineering, 121(8), pp.2129-2142. http://dx.doi.org/10.32604/ee.2024.052280.
20. Saravanan, K. and Ramaswamy, A., 2022, December. Feasibility Analysis for Sustainable Energy Generation from Medium and Large-Scale Industries. In 2022 International Conference on Computer, Power and Communications (ICCPC) (pp. 468-473). IEEE. https://doi.org/10.1109/ICCPC55978.2022.10072116.
21. Karthikeyan, G. and Jagadeeshwaran, A., 2024. Enhancing Solar Energy Generation: A Comprehensive Machine Learning-Based PV Prediction and Fault Analysis System for Real-Time Tracking and Forecasting. Electric Power Components and Systems, 52(9), pp.1497-1512. https://doi.org/10.1080/15325008.2023.2293947.