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# Comparative Analysis of Bio-Inspired Maximum Power Point Tracking Algorithms for Solar Photovoltaic Applications

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**Abstract:** Research and development in Maximum Power Point Tracking in solar photovoltaic systems gains more importance in the modern world. The main issues and challenges in solar photovoltaic systems are partial shading conditions, rapid variations in atmospheric conditions, installation cost, cost of semiconductor material, and poor solar panel power conversion efficiency. More research and development is taking place in Maximum Power Point Tracking to overcome those issues in solar photovoltaic systems. However, most MPPT technics cannot reach their optimum performance to operate PV panels at their maximum available power. To overcome this issue, research is focused on the advanced Maximum Power Point Tracking algorithm and hybrid MPPT algorithm rather than conventional MPPT algorithms. In this research, the advanced MPPT, such as bio-inspired Maximum Power Point Tracking methods, are evaluated based on the speed of convergence, requirements of sensors, robustness and efficiency, tracking efficiency, and tracking accuracy. The comparative results show that the ABC algorithm performs best among other bio-inspired MPPT algorithms in fast-changing atmospheric conditions. In addition, the scope and review of hybrid MPPT in a solar photovoltaic system are discussed in brief.

***Keywords:*** *Maximum Power Point Tracking, Solar Photovoltaic System, Partial Shading, BI-based MPPT*

## 1. Introduction

The energy crisis is one of the biggest challenges faced by the global community. An increase in pollution, depletion of fossil fuel, and global warming lead to a transition of energy scenario from conventional to non-conventional energy. The installed capacity of renewable energy power plants drastically increased in the past decades all over the globe. Regarding salient features like adaptability, zero-noise operation, easiness of installation, expansion of the power plant, reduced maintenance cost, and complexity, solar energy conversion systems dominate among renewable energy sources like wind, biomass, and OTEC. Conversely, there are challenges such as partial shading, intermittency in weather, price hike in the semiconductor material, non-linear characteristics of PV cells, and poor power conversion efficiency. To overcome the challenges especially partial shading conditions and power conversion efficiency, the solar panel is operated at its optimum point using a power electronic interface. The power electronic interface that helps operate the PV panel at its maximum power point tracking is known as maximum power point tracking.

In this regard, researchers developed various MPPT algorithms, broadly divided into conventional and artificial methods. Conventional MPPT is also known as the classical MPPT algorithm. Perturb & Observe (P&O) is a commonly used classical algorithm that is quite simple and easy to implement. However, the algorithm could be more stable in fast-changing atmospheric conditions, and there is rapid oscillation around the maximum power point [1]. To overcome the oscillation issue around maximum power point, a variable step size P&O algorithm is implemented, but variable step size leads to power losses and reduced tracking accuracy [2]. Although the P&O is modified with variable step size, it shows a poor response in the partial shaded condition in connection with the selection of the global maxima point [3]. Another classical MPPT algorithm is the Incremental Conductance Algorithm (ICA) [4], which performs a stable operation in rapidly changing environmental conditions and records better performance than the P&O algorithm [5]. ICA is complex compared to the P&O MPPT algorithm regarding memory size, iteration count, and adaptability. Even if ICA has certain shortcomings compared to P&O, it shows improved performance in partial shading conditions rather than the performance of P&O. However, ICA is not a viable solution and not good enough to meet the requirement of the PV system for optimal operation. Hill Climbing MPPT Algorithm (HCA) [6] also faces similar challenges to the P&O MPPT algorithm. Therefore all the direct classical MPPT algorithms are not an optimal solution for the better performance of the solar photovoltaic system. Indirect classical methods like Constant Voltage (CV) and

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Constant Current (CI) [7] are simple to implement and free from oscillation around MPP in fast-changing atmospheric conditions. However, in the case of CV and CI, prior knowledge of the system and weather conditions is essential. Implementation of these indirect methods merely depends on predefined information on the systems and not a viable solution.

Nowadays, soft computing methods, also known as advanced methods [8], give more attention to implementing efficient MPPT techniques. Advanced methods are divided into Artificial Intelligence-based MPPT (AIMPPT) [9] and bio-inspired MPPT techniques (BIMPPT) [10]. Unlike conventional MPPT, AIMPPT does not need a mathematical system model and deals with variable inputs, self-learning ability, self-convergence capability, and high adaptability. Conversely, the main shortcomings of AIMPPT are the requirement of highly knowledgeable technical staff, the algorithm's success depends on the rule base's design, large memory size requirements, detailed knowledge of the system and weather conditions, and the necessity of tuning in a regular basis. Similarly, Various factors such as temperature variation, changes in irradiance level, partial shaded condition, cost of semiconductor material, and low conversion efficiency are significant challenges for Solar Photovoltaic systems. In the case of bio-inspired MPPT algorithm, high speed of convergence during fast changing atmospheric conditions, detection of global maximum power point using feasible combinations and variables. On the other end, the significant setbacks are the complex mathematical modeling and unwanted power fluctuations due to random variables. The performance varies based on the choice of metaheuristic algorithms (bio-inspired algorithms) adapted for the system. In this regard, a detailed comparative analysis of various BIMPPT is carried out in this research based on performance parameters. In the end, the scope of implementation of the hybrid MPPT algorithm [11] is discussed.

The research paper is organized as follows: section 2 presents the analysis of the bio-inspired MPPT algorithm (BIMPPT), Section 3 presents an evaluation and performance comparison of the BIMPPT, section 4 provides the scope of the hybrid MPPT algorithm and section 5 concludes the research paper.

## 2. Overview of Bio-inspired MPPT Algorithms

Metaheuristic MPPT algorithm or bioinspired algorithm (BIMPPT) is implemented based on the motivation from the activities of biological organisms that leads to optimal system performance. Therefore the concept of optimal performance of biological organisms is applied to the solar photovoltaic system in the form of a maximum power point tracking algorithm. A robust mathematical model is required to implement the BIMPPT algorithm. These algorithms are a subset of the advanced MPPT technique. The main objective of implementing the BIMPPT is to overcome the issue of partial shaded conditions. The main impact of partial shading is the operation of the PV system in the local maxima point instead of the global maxima, which leads to reduced performance of the PV system. An overview of the BIMPPT is discussed below.

### 2.1. GA based MPPT Algorithm

A genetic Algorithm (GAMPPT) [12] is an evolutionary technique used to solve engineering problems. It is grouped into Bio-inspired methods [13]. This method is used for tracking the MPP of a solar photovoltaic module. In Biological science, evolution occurs when there is a change in chromosome number. So the changes in the chromosome create mutation. In a nutshell, GA includes the selection of a sample from the population, changes in the chromosome number, and mutation. In a Solar Photovoltaic system, the selected samples are Panel voltage, Panel Current, Temperature, and irradiance. In the second step, any two samples are combined, and the reason for mutation is. In the second step, an optimized fitness function is formulated related to mutation. The flow chart of GAMPPT is shown in figure 1.

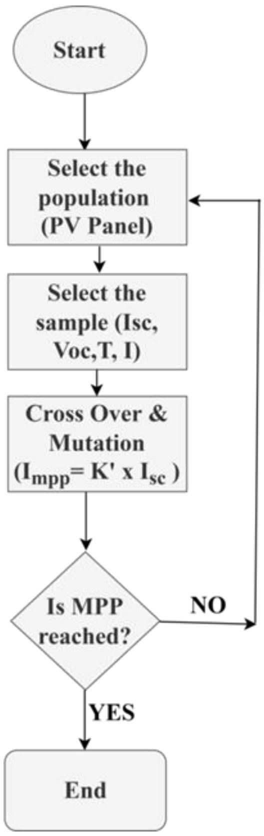


**Fig. 1.** GA based MPPT Algorithm

The population selected for the application is a Photovoltaic solar panel. The selected samples are Open Circuit Voltage ($V_{oc}$), Short Circuit Current ($I_{sc}$), Temperature, and irradiance. The subsequent processes are mutation and cross that produce the maximum current corresponding to the maximum power shown in figure 1. If MPPT is reached, the algorithm helps to operate the PV panel at its maximum power point. If not, a new population will be selected, and repeat the same procedure. Here $I_{mpp}$ is considered as the fitness function. The GAMPPT has a fast operation, but the selection of samples and fitness function is carefully made, or there are chances of an error occurring while optimizing MPP.

### 2.2. PSO based MPPT Algorithm

Particle Swarm Optimisation algorithm (PSOMPPT) [14] is a Bio-inspired algorithm similar to the GAMPPT. PSOMPPT consists of three segments particle, swam, and optimization. A particle is nothing but a population. The swam implies the social behavior of bird flocking or fish schooling. The optimization is nothing but the selection of desired output. The PSOMPPT has no cross-over, mutation, or fitness function [15]. PSO is analogous to flocks of a bird searching for its food particle where the location is unknown. This technique is implemented in a solar photovoltaic system to track the MPP. The general expression for PSO is given in (1)

$$y_i^{n+1} = y_i^n + v_i^{n+1} \quad (1)$$

Where vi indicates a parameter called the 'velocity factor'. The velocity factor is given by (2)

$$v_i^{n+1} = m v_i^n + c_1 r_1 \left(P_{besti} - y_i^n\right) + c_2 r_2 \left(G_{besti} - y_i^k\right) \quad (2)$$

Here $c_1$ and $c_2$ are related to acceleration constants, m denotes inertia weight, Pbest denotes personal best position, and $G_{best}$ is related to the global best position. The parameters of PV panel are considered as the population. Among the population, a sample needs to be selected. Here the voltage is viewed as the chosen sample. Then calculate the duty cycle corresponding to this value. Afterward, calculate the value of $G_{best}$ and $P_{best}$. At a particular point, obtain the value of $G_{best}$ and $P_{best}$. Then the particle is directed towards the $G_{best}$. Once the $G_{best}$ is obtained, the optimum value of voltage corresponding to the maximum power is reached. Here the voltage is considered as the particle. The PSO algorithm is illustrated in figure 2.

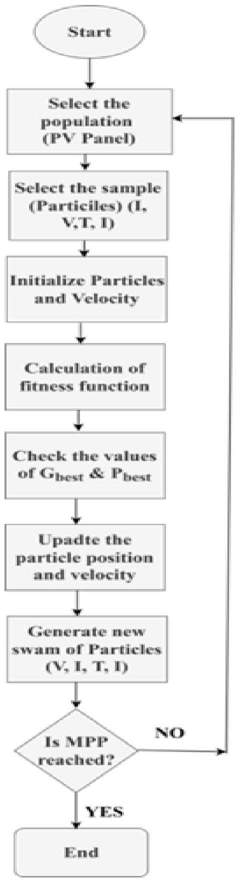


**Fig. 2**. PSO based MPPT Algorithm

PV system is considered as population. Also, the PV panel parameters are considered a sample set. First, in foremost, the particle and velocity are initiated. After that, calculate the fitness functions using equation 15. The $G_{best}$ and $P_{best}$ is calculated, which corresponds to Maximum Power Point (MPP). Then upgrade the position and velocity of the particle and generate the new value of the particle corresponding to MPP. Suppose MPP is not reached, select a new population and redo the procedure. The pros of PSOMPPT are that it is easy to implement, robust, simple, and has no complexity in computation. The main cons of this method are low tracking speed, and the selection of population and samples (particles) are crucial. The wrong choice of a particle causes the error. To improve the tracking speed, a modified PSO MPPT is implemented. Also, PSO can be embedded with conventional MPPT to enhance performance.

### 2.3. ACO based MPPT Algorithm

Ant colony optimization-based MPPT algorithm (ACOMPPT) [16] is a bio-inspired algorithm. It works on the principle of the behavior of ant colonies. Ants are used to find the path of their food using the presence of a hormone called pheromones. Whenever ants start searching for food, pheromones are produced in their path. Usually, the shortest path toward the food can quickly identify analyzing the thickness of pheromone contents. Other ant groups will follow the thicker pheromone path to determine the shortest path of their food. The same principle is applied in the case of the MPPT algorithm. Let us consider the values of current in each module are $I_1$, $I_2$,……$1_n$. The control function can be defined in (3)

$$C = \left[ I_1, I_2, \ldots\ldots\ldots\ldots\ldots\ldots I_n \right] \quad (3)$$

The objective function P(C) is calculated using the mathematical equation (4). P(C) represents the sum of the power of the solar array.

$$P(C) = \sum_{i=1}^{n} \left( I_i \times V_i \right) \quad (4)$$

The sum of power for each module current is calculated and updated in the memory. The iterative solutions are updated in the matrix. The maximum global value of MPP is identified from the matrix. The entire calculation is analogous to following the thickest pheromone path of an ant to determine the shortest way for food particles. The ACO MPPT algorithm is depicted in figure 3.

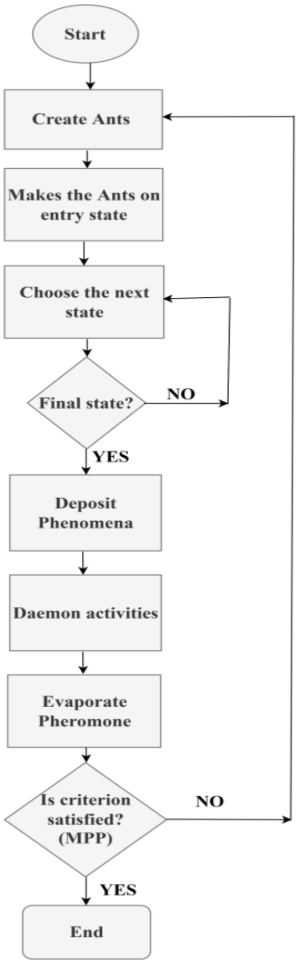


**Fig. 3**. ACO based MPPT Algorithm

Compared to the conventional MPPT technique, ACO shows high tracking accuracy, convergence speed, stability during the partial shaded condition, reduced oscillation around the MPP, and cost-effectiveness.

### 2.4. GWO based MPPT Algorithm

Gray Wolf Optimization (GWO) algorithm (GWOMPPT) [17] is developed in a similar way to the hunting and organizational behavior of Gray Wolf in real life. This meta-heuristic MPPT algorithm defines Gray wolves' hierarchy into four segments in the pyramid fashion shown in figure 20. The segment of the pyramid is Alpha (α), Beta (β), Delta (δ), and omega (ω), respectively.

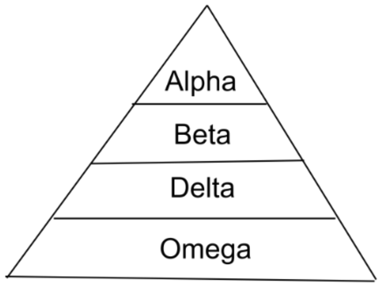


**Fig. 4.** Grey Wolve's pyramid of hierarchy

The wolf belongs to Alpha (α) leads, and Beta (β), Delta (δ), and omega (ω) are the subordinates in the group. The function of wolf Beta (β) is to assist Alpha (α) in decision-making & collect the information from Delta (δ) and omega (ω). The function of Delta (δ) is to take care of other wolves. The process of least rated wolf omega (ω) is to initiate an attack on pray. The team leader of wolves is Alpha (α), which gives the optimum solution. In the MPPT algorithm, the wolf (α) is analogous to MPP.

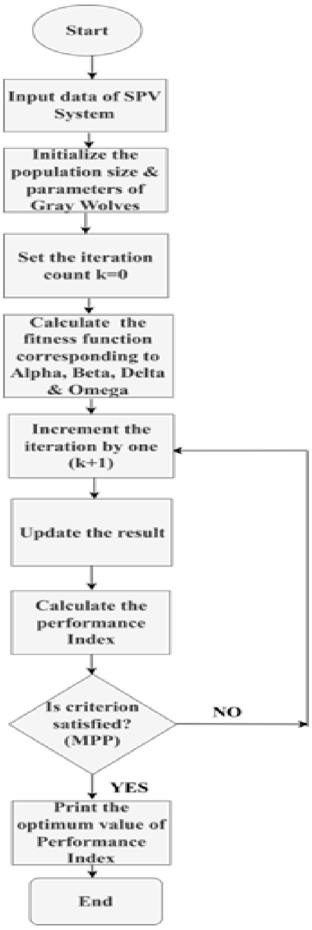


**Fig. 5**. Gray Wolf MPPT Algorithm

The flow chart of the Gray Wolf algorithm is depicted in figure 5. The MPP is reached corresponding to the value of Alpha (α). The GA algorithm shows better-tracking speed and accuracy compared to the conventional algorithms. Also, oscillations are reduced at MPP. However, fixing the duty ratio is one of the difficulties in this type of Algorithm. To overcome this issue enhanced GA algorithm is to be used.

### 2.5. CS based MPPT Algorithm

Xin-She Yang and Squash Deb developed the Cuckoo Search (CSMPPT) Algorithm [18] in 2009, which is applied in the domain of the Indirect MPPT algorithm. The CSMPPT is implemented based on the concept of brood parasitic mechanism. The CSMPPT is similar to P&O MPPT, but the step size of this algorithm is small. Also, it is a population-based algorithm. Here the current and voltage are to be measured to calculate the available from the PV panel, which is used to regulate the fitness function. The duty cycle (D) corresponding to the fitness function is to be calculated, called the best value of the Duty cycle ($D_{best}$). The levy fight is another criterion for this algorithm, leading to a new nest. In a leavy fight, the host bird destroys the egg of the Cuckoo, which leads to finding the best perch. The algorithm stops when the Cukoo finds the best net, which is referred to as the global power. The temperature, irradiance, and partial shading variation represent the levy fight.

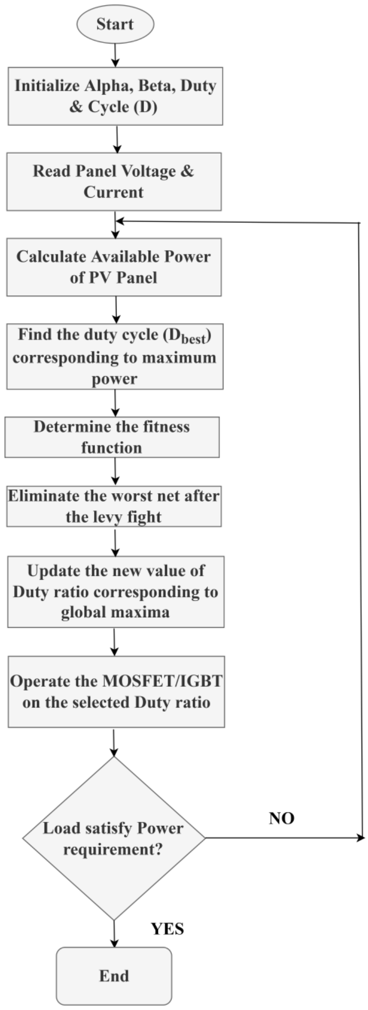


**Fig. 6.** CS MPPT Algorithm

The CSMPPT algorithm usually reaches MPP within 300 ms despite changes in environmental conditions and partial shading. The study says that the tracking accuracy of CS MPPT is three times greater than direct MPPT methods. The algorithm of Cuckoo Search (CS) is given in figure 6. The setback of CS MPPT is random steps, leading to reduced tracking accuracy for some situations. The above-mentioned issue can be mitigated by using the Improved CSMPPT.

### 2.6. ABC based MPPT Algorithm

The Artificial Bee Colony (ABCMPPT)[19] is a population-based stochastic algorithm that follows the behavior of the bee community. This can help to solve optimization problems, especially in MPPT. Their whole bee population is being segmented into three: employed bees, on-looker bees, and last scouts. The job of employed bees is to collect food, on-looker bees make decisions, and last, scouts find a new food path. These three sub-classes help to find the foods optimally.

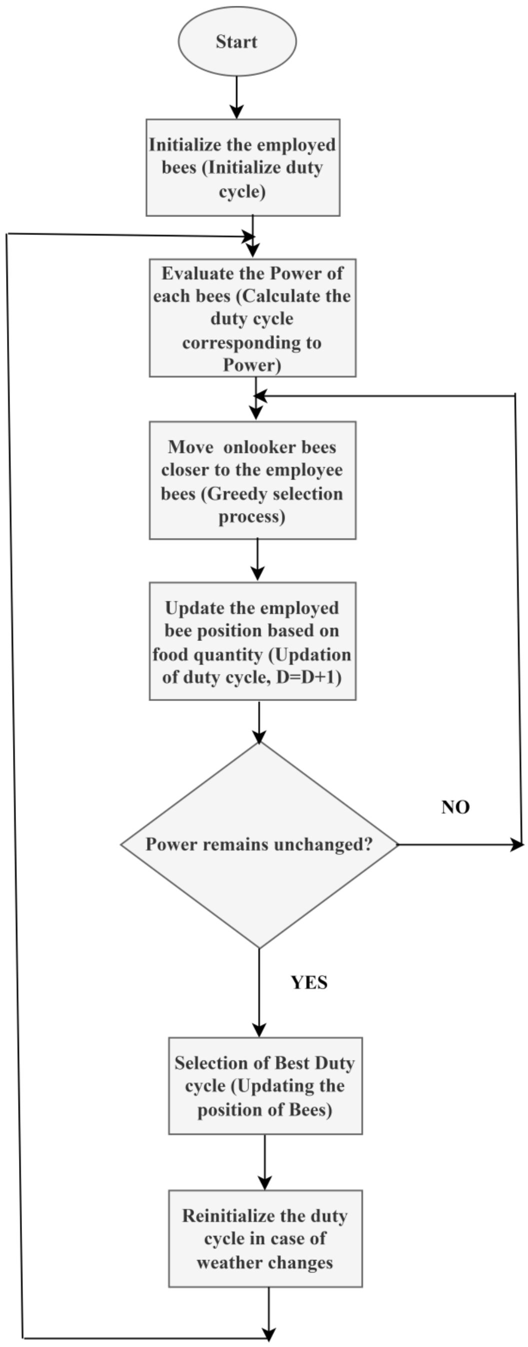


**Fig. 7.** ABC based MPPT Algorithm

Figure 7 depicts the flowchart of ABCMPPT [20]. Here food position indicates the duty cycle, and food denotes maximum power. The duty cycle varies in the range of $D_{max}$ and $D_{min}$. The duty cycle is corelated to maximum power is fed to the DC-DC converter's MOSFET/IGBT switch [21]. The duty cycle is estimated using the mathematical expression in (5).

$$D_i = D_{\min} + rand[01]\left(D_{\max} - D_{\min}\right) \quad (5)$$

The ABCMPPT shows better tracking accuracy and speed than GAMPPT and P&O MPPT algorithms [22]. Moreover, ABCMPPT is one of the best methods of MPPT technique during the partially shaded condition. Therefore ABCMPPT is appropriate for solving optimized problems.

### 2.7. Firefly MPPT Algorithm

The firefly MPPT algorithm (FAMPPT) [23] is a population-based algorithm that follows the behavior of fireflies. The primary functions of fireflies are to attract prays and mates. The attraction of fireflies is based on their brightness and random movements. The flowchart of firefly algorithm is shown in figure 8.

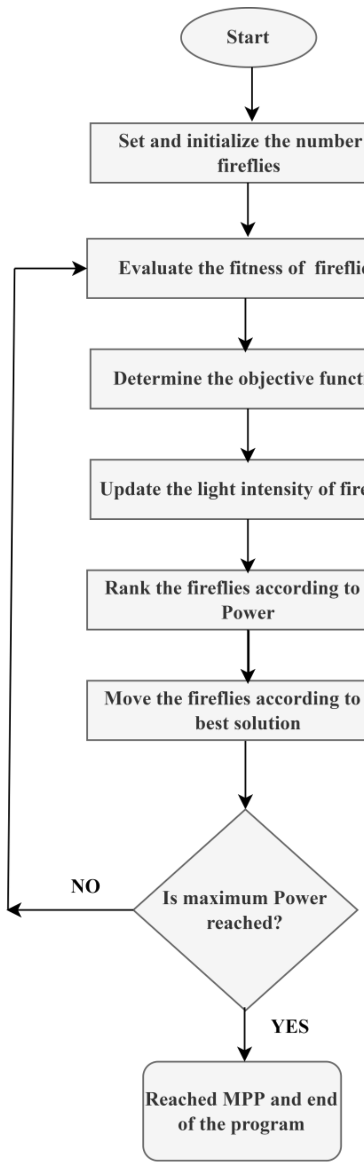


**Fig. 8.** Firefly based MPPT Algorithm

The number of fireflies represents the duty ratios. These duty ratios correspond to local maxima points. Among local maxima points, a global maxima point is selected. The best solution represents global maxima points. A firefly-based algorithm's advantages are: easy to implement, high speed of convergence, saving of microcontroller cost, and high tracking efficiency. The major drawbacks are: that fireflies catch obstacles, and variable step sizes lead to variations in convergence speed. To overcome the above setbacks, a modified firefly algorithm has been developed.

## 3. Hybrid MPPT Algorithm

In most cases, a single MPPT algorithm cannot satisfy all the performance parameters. More than one technique is employed to improve the performance parameters. MPPT algorithm, which is formed by using two or more MPPT algorithms, is known as a Hybrid MPPT algorithm. There are different hybrid topologies, such as two conventional MPPTs, Two advanced MPPTs, and one conventional and one advanced MPPT technique. Hybrid MPPT algorithms [24]-[27] are Hybrid P&O and Incremental Conductance MPPT Algorithm, which help develop the variable step size MPPT Algorithm. Both algorithms are conventional types.

Another example is a combined Incremental Conductance Algorithm and Open circuit-based MPPT. The combined neural and fuzzy logic MPPT is an example of a Hybrid soft computing method. The hybrid PSO and P&O MPPT algorithm [28] is another example of a Hybrid MPPT algorithm that includes one conventional form and another soft computing technique. The Hybrid MPPT algorithm shows the advantages of two types of MPPT algorithms & improves the performance parameters. However, selecting two or more algorithms is difficult as there is no standard procedure for that purpose. A few hybrid algorithms are discussed here.

### 3.1. RZALMS algorithm

RZALMS [29]-[30] algorithm is a predictive control-based approach. The main intention of this method is to minimize the noises produced by the P&O algorithm. Suppose the step size of the P & O MPPT algorithm is less; more time is required to reach the Maximum Power Point. Due to this fact, more power losses take place, which adversely affects efficiency. Conversely, a high step size creates more oscillation around the Maximum Power Point. This creates poor tracking accuracy and confusion. Therefore, P&O is not liable for the fast-changing environment and partial shaded conditions. As the sensor requirement is high, the noise level at the output is also high. To overcome the isses of noise at the output, the P&O MPPT algorithm is embedded with RZALMS algorithm. The basic block diagram of the RZALMS algorithm is picturized in figure 9.

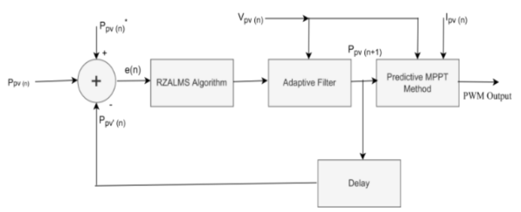


**Fig. 9.** RZALMS based modified P&O MPPT algorithm

RZALMS algorithm is added with the P&O MPPT algorithm to improve the performance. The block diagram includes Predictive MPPT with an adaptive filter; those segments minimize losses and maintain the original signal. The power output of the PV panel is related with the reference signal and produces the error signal, which is given to RZALMS algorithm shown in figure 9. The adaptive filter [31] generated a new power signal indicated by $P_{pv(n+1)}$. PWM output is produced by considering the values of $P_{pv(n+1)}$, $P_{pv(n)}$, and $P_{pv(n)*}$. The noises are drastically reduced at the output and stable during the fast-changing atmospheric condition. This method is quite expensive due to the presence of an Adaptive filter.

### 3.2. D-Sweep Incremental Conductance MPPT algorithm

The setbacks of ICA MPPT algorithms are the requirement of current and voltage sensors; Implementation is complex because a large processor size is essential with high computation speed, such as Digital Signal Processor (DSP) [32]. ICA shows poor performance in partial shaded conditions [33]. However, compared to the P&O MPPT algorithm, the ICA algorithm performs better. Like the P&O MPPT algorithm, variable steps in ICA help to enhance the tracking speed. However, the optimal selection of steps is mandatory. There are two ways of step size selection: Steps are selected initially or through successive segmentation of steps. If the user selects the wrong step size, the algorithm searches the power in the wrong direction and creates power losses. This scenario takes place in partial shaded conditions. To overcome this problem, D-sweep techniques [34] are introduced. The flow chart and features of D-sweep techniques are described below: In case ICA directs a local maxima point, the algorithm fails to reach its maximum power point. To overcome the issue of local maxima, the Duty Cycle Sweep technique is added to the ICA algorithm shown in figure 11.

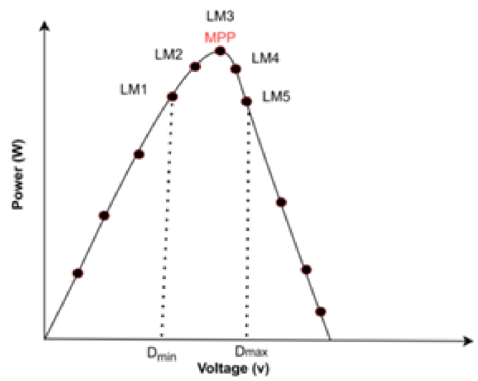


**Fig. 10**. PV Curve with local & global maxima

Figure 10 represents the P-V characteristics of Solar panels with local and global maxima [35]-[38]. Here LM1, LM2, LM4, and LM5 denote local maxima, and LM3 indicates global maxima. During the partial shaded condition, the ICA algorithm wrongly reaches the local maxima instead of the global maxima. To overcome this issue, the duty cycle sweep takes place from $D_{min}$ to $D_{max}$ shown in figure 10. The initial step is to increment the duty ratio. After that, measure the present power. Compare the current power with the previous value of power. The considerable value of power is to be stored in the memory. Check for the maximum value of duty cycle $D_{max}$. If the maximum value of the duty cycle ($D_{max}$) is reached, send the more extensive power duty ratio to the ICA MPPT algorithm illustrated in figure 11. If the value of $D_{max}$ is not achieved, go for an increment in the duty ratio.

The implementation of the D-sweep technique in the ICA algorithm is shown in figure 12. Initially, check the overflow of the timer; if there is no timer overflow, ICA MPPT starts directly. If the timer overflow takes place, the D-sweep technique starts functioning. The D-sweep technique's first step is setting the $D_{min}$, step size, and power.

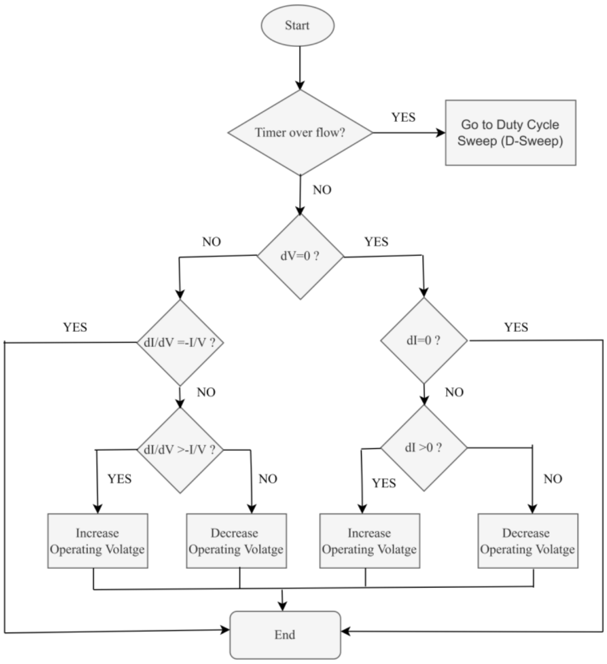


**Fig. 11.** Flow chart of modified Incremental Conductance Algorithm with D-Sweep technique

Later, compare the present power and duty cycle with the previous instant. After that, increment the step size and increase the duty cycle to the step, as shown in figure 11. If the step is greater than the maximum step, ICA MPPT is started, sets the new power value, and checks the unique value of power to the previous value. Suppose the new value of power is larger when compared to the last value, update the new value of power and the corresponding duty ratio. If not, go back to the previous step, i.e., increment the duty cycle and step size shown in figure 12.

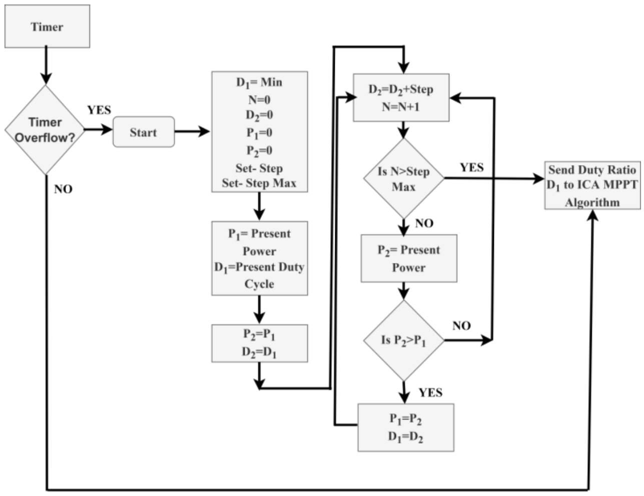


**Fig. 12**. steps involved in D-sweep technique

There are a few more hybrid combinations are mentioned here: To overcome the drawback of P&O, such as oscillation around MPP and low tracking speed, researchers implemented a hybrid ICA-P&O algorithm is implemented. The hybrid ICA-P&O algorithm shows improved tracking speed and reduced oscillation in and around maximum power point. Here both algorithms are conventional. Also, to improve the poor performance of P&O in rapidly changing atmospheric conditions, a hybrid P&O-constant voltage method is developed. In this method, two loops are considered where the loop corresponding to the constant voltage method helps to compute the position of the maximum power point, and the P&O loop is for tuning. Here, P&O is an online method, and the constant voltage method of MPPT is offline. Another solution for tracking global maxima from the multiple local maxima is the hybrid ICA-open circuit voltage MPPT method. Hybrid ABC-P&O is another combination that utilizes the feature of ABC to track global maxima points during partial shaded conditions and avoid the confusion happening in the P&O. Hybrid neural-GA-Fuzzy is an algorithm that utilizes the advantageous features of three algorithms. Solar data optimization is carried out using GAMPPT. Later, the neural network is used for training the optimized data. Therefore, the overall response time is improved, reduced ripple counts, improvement in tracking accuracy, and improvement in tracking efficiency are observed. Moreover, the Hybrid neural-GA-Fuzzy algorithm performs stable operations regardless of changes in the loading.

Nevertheless, the implementation of this algorithm is complex and expensive. It is not affordable for a large solar plant. More research and development are required

**Table 1.** Performance comparison of BIMPPT Algorithm

| *Sl.No* | *BIMPPT techniques* | *Tracking efficiency (%)* | *Tracking accuracy* | *Speed of convergence (ms)* |
|---|---|---|---|---|
| 1 | GAMPPT | 96 | Medium | 0.5 |
| 2 | PSOMPPT | 95 | Medium | 1.3 |
| 3 | ACOMPPT | 95 | High | 0.8 |
| 4 | GWOMPPT | 97 | High | 0.9 |
| 5 | CSMPPT | 96 | Medium | 0.9 |
| 6 | ABCMPPT | 98 | High | 0.3 |
| 7 | FAMPPT | 98 | High | 0.3 |

to reduce the cost of the Hybrid neural-GA-Fuzzy algorithm in SPV applications.

## 4. Results and Discussion on the Performance Comparison of BI-based MPPT Algorithms

There is no thumb rule to evaluate the performance of BIMPPT. Nevertheless, using the experimental data carried out by the researcher and the simulation model, the performance parameters of BIMPPT can be compared. However, the performance parameters such as convergence speed, Periodic tuning, oscillation around MPP, complexity, robustness, efficiency, tracking speed, and cost of implementation can be considered before choosing a suitable algorithm. The comparison of BIMPPT techniques is illustrated in Table 1.

Tracking efficiency is an essential parameter for selecting the MPPT algorithm. In this regard, by referring to table 1 and figure 13, it is clear that all BIMPPT algorithms show better tracking efficiency. Among seven types of BIMPPT, ABCMPPT and FCMPPT shows the highest tracking efficiency. Even ABCMPPT and FCMPPT algorithm dominates in tracking accuracy as well. The analysis shows that GAMPPT and PSOMPPT shows moderate tracking accuracy. However, the selection of samples and fitness function is carefully made in case GAMPPT and PSOMPPT algorithm needs to be embedded with P&O MPPT to enhance the tracking accuracy.

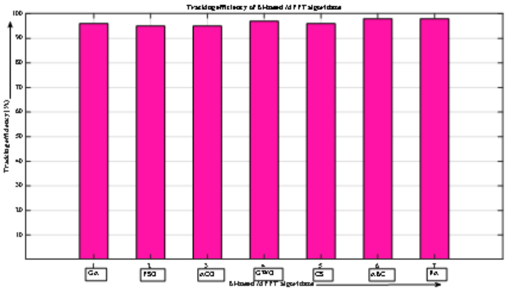

**Fig. 13.** Tracking efficiency of BI-based MPPT algorithms

Tracking efficiency is an essential parameter for selecting the MPPT algorithm. In this regard, by referring to table 1 and figure 13, it is clear that all BIMPPT algorithms show better tracking efficiency. Among seven types of BIMPPT, ABCMPPT and FCMPPT shows the highest tracking efficiency. Even ABCMPPT and FCMPPT algorithm dominates in tracking accuracy as well. The analysis shows that GAMPPT and PSOMPPT shows moderate tracking accuracy. However, the selection of samples and fitness function is carefully made in case GAMPPT and PSOMPPT algorithm needs to be embedded with P&O MPPT to enhance the tracking accuracy.

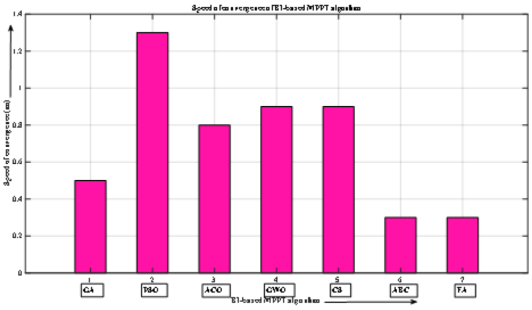


**Fig. 14.** Speed of convergence of BI-based MPPT algorithms

The speed of convergence is an essential factor in rapidly changing atmospheric conditions. An MPPT method is said to be stable; it must have a quick convergence speed. That means, within a short duration of time, a maximum power point has to be reached. In figure 14, it is clear that ABCMPPT and FAMPPT can reach maximum power point compared to other MPPT algorithms. PSOMPPT takes more time to reach MPP compared to other types of BIMPPT. A few crucial parameters, such as cost of implementation, complexity, the requirement of periodic tuning, oscillation around maximum power point, and dependency on PV array characteristics, are to be inspected. The literature says that all the BIMPPTs are complex and expensive. High technical knowledge is required to implement all the BIMPPT techniques. In the case of BIMPPT, the prior knowledge and dependency of PV array are not necessary, unlike the AIMPPT algorithm. In most cases, no oscillation around the maximum power point is observed. Furthermore, periodic tuning is not required, unlike the AIMPPT algorithm.

All the BIMPPTs are treated as offline methods. To implement BIMPPT, current and voltage sensors are also essential.

## 5. Conclusion

An overview of BIMPPT algorithms is carried out using test results and literature. The performance parameters such as convergence speed, periodic tuning, oscillation around MPP, complexity, robustness, efficiency, tracking speed, and cost of implementation are considered while performing comparative studies. Overall performances of BI-based MPPTs are superior to classical MPPT algorithms. The tracking efficiency of BIMPPTs is above 90%. Although the superior performance of BIMPPT, the cost of implementation and complexity are the major constraint. While inspecting the comparison among BIMPPT, ABCMPPT and FCMPPT shows the best performance regarding tracking efficiency and convergence speed. Also, shortcomings of individual methods can be overcome using hybrid MPPT methods. The Hybrid Neural-GA-Fuzzy MPPT algorithm gives superior performance to combinations such as RZALMS algorithms, D-sweep MPPT, Hybrid ICA-P&O algorithm, Hybrid P&O-constant voltage, ICA-open circuit voltage MPPT, and Hybrid ABC-P&O method. However, the real-time development of the Neural-GA-Fuzzy MPPT algorithm is a cumbersome task concerning the cost of implementation and complexity. The selection of optimal hybrid MPPT, reduction in the implementation cost, and development is considered crucial research work in the future.


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### Author contributions

**Vineeth Kumar P K:** Conceptualization, Methodology, Software, Field study, Data curation, Writing-Original draft preparation

**Dr.Jijesh J J:** Visualization ,Software, Validation, Investigation, Writing-Reviewing and Editing.

### Conflicts of interest

The authors declare no conflicts of interest.

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