ISSN (e): 2250 – 3005 || Volume, 15 || Issue, 8|| August – 2025 ||
International Journal of Computational Engineering Research (IJCER)

An In-Depth Survey of Techniques for Maximum Power Point Tracking in Solar PV Systems

Manoj Kumar [1] , Vinay Kumar[2]
Scholar M.Tech[E.E.][1] , Scholar M.Tech[M.E.][2]
Vishveshvarya Group of Institutions, Greater Noida

Abstract- *The integration of solar photovoltaic (PV) systems into multimachine power systems presents both opportunities and challenges for ensuring grid stability amid dynamic disturbances. The PV-STATCOM, a hybrid configuration combining PV inverters with Static Synchronous Compensator (STATCOM) capabilities, enhances reactive power support and voltage regulation. This review synthesizes advancements in PV-STATCOM applications, with a focus on soft computing techniques such as Particle Swarm Optimization (PSO), Bacterial Foraging Optimization Algorithm (BFOA), and hybrid metaheuristic algorithms for controller optimization. Analysingrecent peer-reviewed articles, this paper evaluates the evolution of control strategies, their impact on transient and voltage stability, and integration challenges in multimachine environments. Findings underscore the efficacy of hybrid optimization algorithms in addressing nonlinear grid dynamics, though gaps persist in scalability, real-time implementation, and cybersecurity. Future research should explore advanced algorithms, energy storage integration, and hardware validation to broaden PV-STATCOM's applicability in modern power systems.*

I. INTRODUCTION

To date, the provision of access to electricity to all continues to be a ripe challenge in the world. Therefore, there has been intensive research into the development of cleaner and efficient power-generating means. This ranges from the development of alternative sources of energy and improvement of current generation systems to maximize performance and minimize costs [1-4]. The switch to eco-friendly energy solutions is also available due to the scarcity of fossil fuels traditionally used in generating power [5]. Traditional coal and thermal power stations have negative impacts on the environment, thus, renewable energy (RE) technologies are a more sustainable option for the energy sector in the future [6,7]. Hybrid systems, where various sources of energy are combined to supply the energy needs, also improve supply reliability [8-14]. However, such sources of renewable energy, being natural, are not consistent, just like the weather. This is characterized by shifts in the amount of sunlight or the velocity of the wind [12]. Solar photovoltaic (PV) systems, which convert sunlight to electricity, through solar panels, also have their drawbacks in that their energy conversion efficiency is not high [15-23]. Therefore, various state- of-the-art control strategies are being applied to get the optimum power from these renewable systems.

For PV systems, the Maximum Power Point, or MPP, refers to the point of greatest solar energy production. There is a dynamic connection between this point and the physical environment, including the irradiance and temperature of the sun. As PV systems are designed for a specified amount of power delivery under standard conditions, changes in the environmental parameters can have a strong impact on their performance [24-28]. To extract maximum energy, the PV system needs to operate under MPP, which is the point attained at the maximum value of the product of current and voltage at any time on the power-voltage (P–V) curve.

The MPP must be tracked by Maximum Power Point Tracking (MPPT) algorithms to keep operation at an optimal level [29]. These algorithms constantly change the conditions of operation, orienting them to the change in the MPP, therefore obtaining the maximum amount of energy from PV modules. The main task of MPPT techniques is to keep the derivative of power with respect to voltage at zero value, which means MPP on the P–V curve [30]. This is usually done by measuring the output current and voltage of the PV array. In addition, it adjusts the duty cycle of the DC- DC converter to match the source impedance with the load. Correct impedance matching allows for better MPP tracking.

When utilizing MPPT strategies, the following advantages are significant: enhanced efficiency and higher energy output from PV systems [31]. However, one of the key issues is precisely monitoring voltage fluctuations and dynamically varying the duty cycle on the fly to extract maximum power [32-39]. Figures 1 show the volatilities of voltage, current, and power outputs of a typical PV module due to changes in solar irradiance and temperature. This emphasizes the need for efficient MPPT mechanisms.

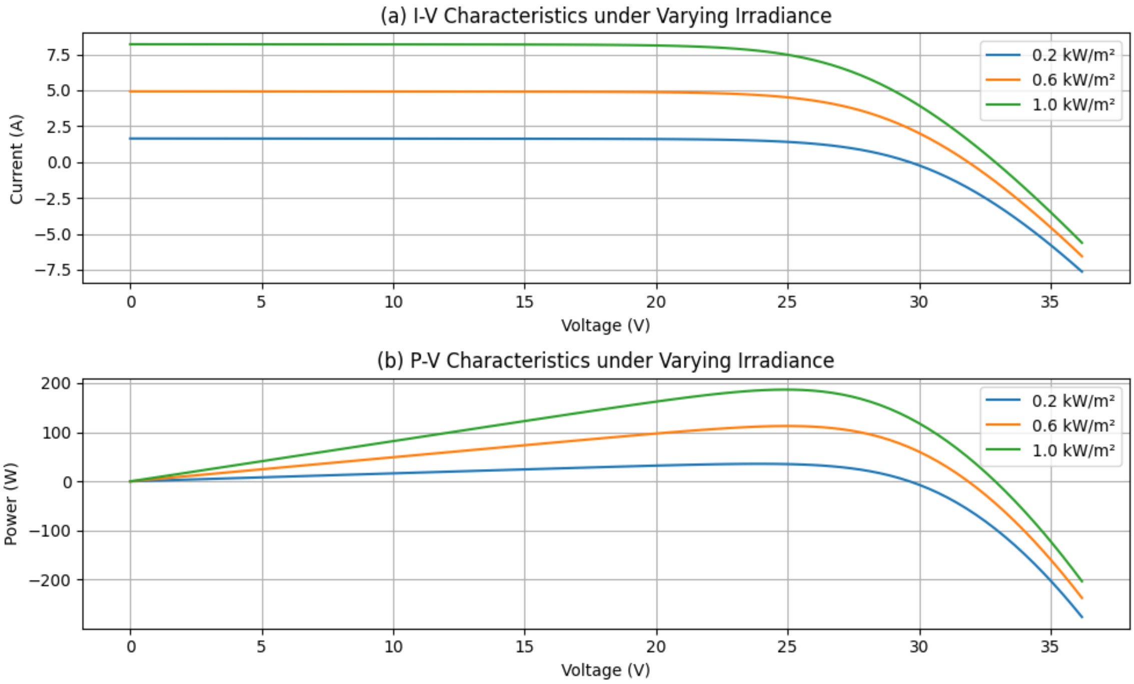

Figure 1. (a) I-V and (b) P-V characteristics of a solar module under varying temperature.

The above data shows that temperature changes tend to affect the voltage of a solar module more than its current. On the other hand, changes in solar energy hitting the module affect its current by more than they affect the voltage. The power coming from the solar panel is also affected by either situation [40].

Furthermore, the I-V and P-V curves of PV modules are not the same when exposed to sunshine as when some of their cells are shaded. Variation occurs because the amount of voltage and power in a PV module changes according to sunlight intensity and temperature [41,42]. The maximum power point in the I-V and P-V curves is plain and doesn't change, regardless of how bright the light is. Yet, with partial shading, the curves show several local maxima [43], making it complicated to find the highest power point.

Generally, MPPT approaches are divided into four categories depending on the way they track the MPPT point: classical, intelligent, optimization-based, and hybrid methods [44-59]. Each MPPT technique is more effective if it can handle environmental changes and reliably find the highest energy output. The comparison of the MPPT categories is collected in Table 1.

II. TRADITIONAL METHODS FOR MPPT

MPPT using traditional methods is recognized for being simple and easy to implement. They produce the best electricity when the sun is shining consistently. Nevertheless, the movements around the MPP while the device is running may lessen the system's efficiency. Besides, these approaches fail to include the impacts of partial shading, so finding the right MPP is often hard when shading is involved [49,57].

2.1. Perturb and Observe (P&O) MPPT Techniques

Commercial MPPT systems use the P&O technique more often than any other method [44,58]. With this approach, you should monitor how the power output (dP) of the PV module changes. In addition, changes in voltage (dV) are used to determine and set a new duty cycle (D), which helps the system regulate the load current. To make the needed adjustments, the scientists rely on the PV module's power-voltage (P-V) curve.

When the gradient is moved to the left, it means that the operating point is ahead of the MPP on the graph. A downward gradient means that the MPP is situated towards the left of that point. The process repeats itself until the line flattens out, which means that the MPP is now reached. The speed at which these disturbances happen each second is named the perturbation frequency, which is also used to define the MPPT frequency dP/dV [60,61].Equations (1)to (3) are used in the Perturb and Observe (P\&O) technique for making voltage adjustments. The most critical difference when using this method is whether the step size in the duty cycle is the same all the time or is adjusted as needed.

In this method, the PV power at a specific time is compared to the power measured at the previous moment. Based on the difference (ΔP), the duty cycle is then chosen. Therefore, the converter is prompted to make a specific change, either upward or downward, in the voltage, V(t).The P&O approach is widely found in both fixed and adaptive steps [58].Figure 2 displays the flowchart for the P & O method.

$P(t) = V(t) \times I(t)$ (1)
$Delta = P(t) - P(t-1)$ (2)
$V(t) = V(t-1) \pm \Delta V$ (3)

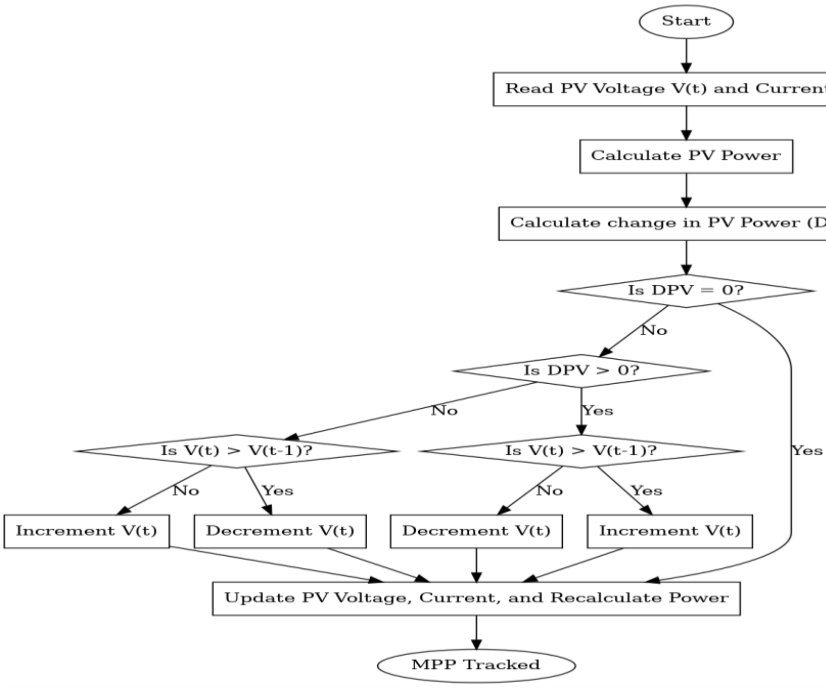

Figure 2. Flow chart for P&O method.

Table 1. Overview of MPPT technique categories (adapted using information from [44]).

Class	Sub-Class	Acronym
Classical MPPT control techniques	Perturb and Observe	P&O
Classical MPPT control techniques	Constant Voltage	CV
Classical MPPT control techniques	Ripple Correlation Control	RCC
Classical MPPT control techniques	Hill Climbing	HC
Classical MPPT control techniques	Improved Perturb and Observe	IP&O
Classical MPPT control techniques	Short Circuit Current	SCC
Classical MPPT control techniques	Open Circuit Voltage	OCV
Classical MPPT control techniques	Adaptive Reference Voltage	ARV
Classical MPPT control techniques	Incremental Conductance	InC
Classical MPPT control techniques	Look-Up Table-Based MPPT	LTB MPPT
Intelligent MPPT control techniques	Artificial Neural Network	ANN
Intelligent MPPT control techniques	Fuzzy Logic Controller	FLC
Intelligent MPPT control techniques	Sliding Mode Control	SMC
Intelligent MPPT control techniques	Fibonacci Series-Based MPPT	FSB MPPT
Intelligent MPPT control techniques	Gauss Newton Technique	GNT
Optimization techniques	Particle Swarm Optimization	PSO
Optimization techniques	Cuckoo Search	CS
Optimization techniques	Artificial Bee Colony	ABC
Optimization techniques	Ant Colony Optimization	ACO
Optimization techniques	Grey Wolf Optimization	GWO
Optimization techniques	Genetic Algorithms	GA
Hybrid techniques	Adaptive Neuro Fuzzy Inference System	ANFIS
Hybrid techniques	Fuzzy Particle Swarm Optimization	FPSO
Hybrid techniques	Grey Wolf Optimization Perturb and Observe	GWO-P&O
Hybrid techniques	Particle Swarm Optimization Perturb and Observe	PSO-P&O
Hybrid techniques	Hill Climbing Adaptive Neuro Fuzzy Inference System	HC-ANFIS

2.2. Application of the Hill Climbing (HC) Algorithm

With the HC technique, the duty cycle of the power converter is changed to follow the MPP. In practice, this technique is not the same as Perturb and Observe (P&O). In the P&O system, the voltage curve of the PV module is disturbed, while in HC, the converter's duty cycle is adjusted straightaway for maximum power point tracking [62]. As the PV system reduces its output, the system will adapt the duty cycle much more easily to help the system achieve the highest output. Based on how the power changes, the duty cycle is adjusted so that the algorithm remains on the right part of the module's P-V curve. The adjustments to duty cycle are covered by Equation (4).

$$D(i) = D(i-1) \pm S \quad (4)$$

In the ith iteration, the converter is regulated by $D(i)$, and $D(i-1)$ shows the duty ratio from the previous step $(i-1)$. S, referring to the step size, determines how much each step alters the solution. It can stay the same or can change depending on the chosen algorithm. The chosen sign for S is based on where the power point lies on the characteristic curve. If both voltage and power experience a similar increase or decrease, S takes a negative number. In the case where the changes in power move in the opposite direction, S is set to a positive value.

2.3. Open Circuit Voltage is known as OCV.

By multiplying the solar modules' open-circuit voltage (Voc) by a value between 0.7 and 0.8, the open-circuit voltage (OCV) method can calculate the voltage at the Maximum Power Point (MPP) [74]. While the method is easy to use, every time Voc is measured, the load must be disconnected first. As a result of this issue, the supply of electricity may be interrupted, making the system run less efficiently [75]. Therefore, this method should not be chosen when supplying steady power to the load is important.

2.4 Adaptive Reference Voltage (ARV)

Adaptive Reference Voltage (ARV) controls the feed rates during the growing process, considering the changes in temperature and solar radiation. As a result, extra sensors are put in place to measure these things as well as voltage. For person temperature, only seconds, the radiation is split into several ranges, with the valuable references stored in a separate database. A PI controller is responsible for determining the duty cycle needed to achieve the difference between the PV voltage and the reference voltage. As shown in [77], ARV works well even when the sun's energy fluctuates.

2.5 The Idea of Incremental Conductance (InC)

Incremental Conductance(InC) is a standard method that is used to identify the MPP in photovoltaic systems. By measuring current and voltage on the PV module, the MPP can be determined regardless of changes in the weather. The mathematics of this method is detailed in Subudhi et al. [56]. Even though the approach is more difficult than the Perturb and Observe (P&O) method, recent improvements in Digital Signal Processors (DSPs) now make it easier to use.

III. INTELLIGENT MPPT CONTROL METHODS.

The systems rely on soft computing to perform the function of maximum power point tracking (MPPT).

They are regarded as more advanced because they apply machine learning to control their strategies.

3.1 Artificial Neural Network (ANN)

Artificial Neural Networks (ANNs) are based on the functioning and structure of the human brain. The network is built with connected neurons (nodes) that gain knowledge from data by adjusting the weights in the connections [52,80]. Figure 3 depicts the typical ANN structure which consists of the input, hidden and output layers. Data can be fed into the network from external sources such as temperature or lighting and also from product variables such as Voc and Isc. The network output controls the pulse-width of the waveform to follow the MPP that is determined by the hidden layer. Through practice, the connections between neurons are adjusted by using data from past observations.

Nevertheless, this method can only be used for individual PV modules since the network is not general enough. Since the properties of PV panels vary with time, it is necessary to retrain the network frequently so it can track MPP accurately [50]. Additional study should test if an algorithm founded on an ANN for one PV system can be used on other similar systems without changing it.

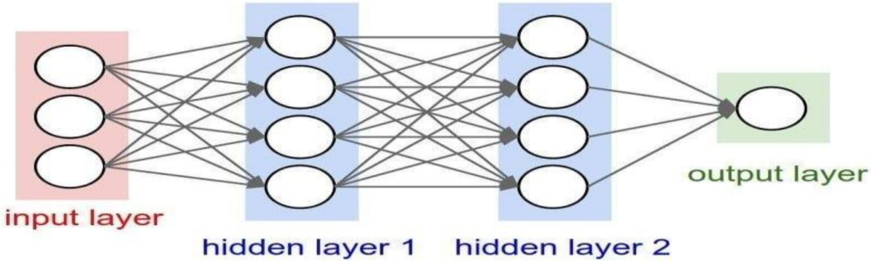

Figure 3: Layers of ANN

3.2 Procedure for a Fuzzy Logic Controller (FLC)

In contrast to binary logic with two states (true and false), fuzzy logic lets there be values ranging from 0 to 1. This means that a condition can have aspects that are both correct and incorrect [52]. Fuzzy logic-based MPPT methods are considered intelligent since they continue to locate MPP even if the input data is unreliable. A benefit of fuzzy logic controllers is that a complex mathematical description of the system is not necessary.

As a rule, fuzzy control systems make use of these three main procedures: fuzzification, rule evaluation using a

lookup table, and defuzzification. Numeric values are turned into simple definitions during the process of fuzzification. Typically, inputs are classified into five degrees: (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big). Typically,MPPT applications rely on error (E) and the new error (ΔE) as input parameters, which can be found from specific equations as presented by Ngan and Tan [22].

$$E(i) = \frac{Ppv(i) - Ppv(i-1)}{Vpv(i) - Vpv(i-1)} \quad (5)$$

$$\Delta E(i) = E(i) - E(i-1) \quad (6)$$

ΔD (the change in the duty cycle of the power converter) is produced once E (error) and ΔE (change in error) are turned into linguistic terms. After finishing the fuzzy inference, the next step is defuzzifying the output to get a numerical measurement. Afterward, this final value is used to generate a control signal that ensures the power converter operates on its maximum power point.

The performance of the fuzzy MPPT controller remains effective regardless of the weather [81]. Neural network models are efficient only if the errors are understood correctly and the rule base table is built skillfully [32,50,82] as shown in Table 2. The advantage of this approach is that it gets rid of having to build a mathematical model for the PV system. Furthermore, it increases the stability of the MPP by decreasing oscillations.

Yet, there are some difficulties in using this technique, such as adjusting the membership functions, scaling the parameters, and creating the best set of control rules. More studies are needed to fully benefit from fuzzy logic in MPPT systems.

Table 2: Rules for fuzzy logic

Change in Error / **Error (E)**	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS

PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

3.3 The Gauss-Newton Technique (GNT)

The Gauss-Newton Technique is a renowned method for root-finding due to its impressive speed when compared to other approaches. It derives the solution according to the first and second power variations and estimates the required number of iterations [44, 56]. Still, this technique has one major disadvantage: building the model is very complex since it requires strict mathematical methods. With continued research, this complexity could potentially be reduced to make the method more practical.

IV. OPTIMIZATION TECHNIQUES

Such methods are referred to as metaheuristic optimization algorithms. Because metaheuristic approaches are better than traditional ones, their popularity is increasing. They are extremely valuable because they can address many complex real-world problems, have multiple objectives, and use nonlinear calculations. These algorithms are explained briefly in Table 3.

Table 3: Optimization Techniques

Method	Description	Advantages	Disadvantages
Particle Swarm Opti- mization (PSO) [83]	PSO is inspired by the collective behavior ob- served in flocks of birds or schools of fish. It identifies the global maximum power point (MPP) in a photovoltaic (PV) array by optimiz- ing the converter's duty cycle and output power as the objective func- tion.	Exhibits fast-tracking capabilities even under fluctuating weather and partial shading scenari- os.	The objective function depends heavily on particle velocity, which adds complexity to the optimization process.
Cuckoo Search (CS) [84]	This algorithm mimics the parasitic reproduc- tion behavior of cuckoo birds.	Offers rapid conver- gence and requires few- er tuning parameters compared to PSO, lead- ing to greater robust- ness in performance.	Involves the use of complex mathematical functions within the algorithm.
Artificial Bee Colony (ABC) [85]	ABC draws inspiration from the foraging be- havior of honeybees. It features a simple design with minimal controlla- ble parameters, and its convergence does not depend on initial sys- tem conditions. The maximum power acts as the food source, while the duty cycle repre- sents the food position.	Requires very few pa- rameters to function.	Can be slow in tracking and sometimes only finds local MPP instead of the global MPP.
Ant Colony Optimiza- tion (ACO) [86]	This probabilistic method is based on how ants search for food, and it is applied in both centralized and distrib- uted MPPT controllers to reduce the number of local maxima on the I- V curve.	Provides fast conver- gence, easy control implementation, low cost, and performs well under partial shading conditions.	Relies on a complex estimation method.
Genetic Algorithm (GA) [87]	GA follows principles of natural selection, using evolutionary pro- cesses to optimize. It is used to train artificial neural networks (ANNs) to predict max- imum voltage and cur- rent at the PV array's MPP and to optimize economic design in- volving different in- verters.	Effective at optimizing and training MPPT al- gorithms for rapid and precise tracking.	Tracking speed is gen- erally slower compared to other methods.
Grey Wolf Optimiza- tion (GWO) [88]	This technique is in- spired by the hunting behavior of grey wolves, which hunt in phases:	Demonstrates efficient tracking with no oscil- lations in steady or transient states, along with	Computationally inten- sive, with large search spaces and higher im- plementation costs.

	searching, en- circling, and attacking prey.	robustness and faster convergence.	

V. HYBRID TECHNIQUES

5.1. An adaptive neuro-fuzzy inference system (ANFIS)

A technique that makes use of ANN and FLC to easily find the GMPP is called ANFIS. The reason it is efficient is that its membership functions instantly respond to different input values. Because of this, PV systems that are partially shaded can work very well with this feature. ANN is valuable because it makes tracking more accurate and improves the system's settings. At the same time, FLC ensures that the system can handle nonlinear inputs without needing information about how the system normally behaves beforehand. Still, since its operation is complex, implementing the algorithm increases costs, so it is not as useful for MPPT.[89]

5.2. Fuzzy Particle Swarm Optimization (FPSO)

Fuzzy Particle Swarm Optimization (FPSO) combines the methods of fuzzy logic and the particle swarm optimization algorithm[90]. The result increases the performance of the controller by making tuning parameters more efficient and reducing the amount of computation required. Consequently, the membership is spread out evenly, which results in the system working more efficiently. Using an FPSO decreases the need for a PI controller, helps avoid switching losses, and reduces the system's complexity. However, there is a noticeable problem with how these rules are formed, as they are rigidly developed by hand and often require a lot of trial and error from experts.

5.3. Grey Wolf Optimization with Perturb and Observe (GWO-P&O)

Applying the P&O method with GWO speeds up the process of reaching the GMPP. First, GWO is used to find different solutions, and afterward, P&O works on
the best ones to lower the number of computations. Because the wolves correspond to the duty cycle, the usage of PI controllers is not needed in MPPT methods. If we evaluate the performance of RGWO versus GWO or P&O on their own, the RGWO method is superior for sticking to a target and converges in a shorter time. Nevertheless, the method requires a lot of math, which could cause difficulties when it is applied [91].

5.4. Particle Swarm Optimization with Perturb and Observe (PSO-P&O)

At the start of the tracking process, PSO searches widely, while P&O focuses on adjusting the results. Using this approach improves the speed of GMPP detection and curbs fluctuations in the system's power outflow during tracking [92]. Although it is faster than traditional PSO, it has a complicated structure and might not succeed in converging if the GMPP is outside the area where searches are made. In some cases, this way of development requires a lot of hardware. By handling convergence restrictions and modifying how the search space is set, its quality may increase.

5.5. Hill Climbing with Adaptive Neuro-Fuzzy Inference System (HC-ANFIS)

The hybrid method was created to fix the problems that occurred with hill climbing (HC) and ANFIS. Kamran [93] claims that this way works faster than the conventional methods. To commence, solar irradiance and temperature are involved in the ANFIS model to form a preliminary output. At this point, HC receives the value and adjusts the duty ratio using actual PV voltage and current to produce the best MPPT result at the moment. What this approach offers most is its fast reaction and doing away with creating mathematical models. On the other hand, determining how to create effective membership functions is still a challenge today.

Further improvements might simplify these tasks to make this technology more useful and straightforward.

VI. CRITERIA FOR RANKING DIFFERENT MPPT TECHNIQUES

Since MPPT controllers use many different technologies, they are assessed based on different points.
Ahmad et al. [43] suggest several factors to use when ranking Maximum Power Point Tracking strategies, as you can see in Table 4.

Table4. Criteria for determining MPPT rankings redrawn with data from [43].

Criterion	Considerations	Ranking
Algorithm Complexity	Comparable to the Perturb and Observe (P&O) method	Best
	Slight modifications to P&O, often combining it with other approaches such as bio-inspired or AI-based techniques	Moderate
	Advanced AI or bio-inspired methods that involve intricate designs	Very Complex
Hardware Implementation	DC-DC converter equipped with current and voltage sensors	Best
	Incorporation of PI or PID con- trollers for duty cycle adjust- ments in the converter	Moderate
	Requires advanced embedded system hardware	Very Complex
Tracking Speed	Response time from 0 to 100 milliseconds	Best
	Response time between 100 mil- liseconds and a few hundred milliseconds	Moderate
	Response time ranging from several hundred milliseconds to a few seconds	Very Slow
Efficiency Under Uniform Conditions	Efficiency ranges from 97% to 100%	Best
	Efficiency between 93% and 96.9%	Moderate
	Efficiency below 92.9%	Less Efficient
Accuracy During Partial Shad- ing	Consistently tracks the global maximum power point (GMPP), outperforming MPPT methods of similar complexity	Best
	Unable to track GMPP but per- forms better than standard P&O under shading	Moderate
	Tends to settle on local maxima, similar to P&O	Less Accurate

VII. COMPARATIVE EVALUATION OF VARIOUS MPPT TECHNIQUES

Maximum efficiency in PV systems depends on your choice of an appropriate MPPT controller. Methods for designing MPPT controllers are not the same, since their applications differ. When choosing the most suitable method, we must consider factors such as costs, response time, and efficiency. The analysis of MPPT techniques is carried out by comparing various characteristics, like the expense to implement, complexity in the circuit, speed of response, how much tuning is necessary, parts used for sensing, stability, accuracy, and their performance while shaded. Also, Figure 4 illustrates the efficiency results of different MPPT approaches described in existing papers. Comparison summary is shown in Table 5.

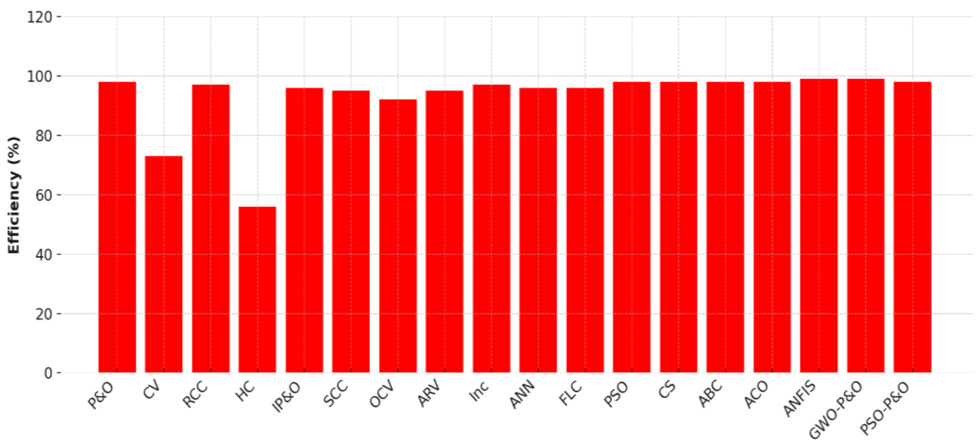

Figure 4: Efficiency of different techniques for MPPT. Table 5: Comparison Summary of Techniques

Table 5: Comparison Summary of Techniques

MPPT Method	Cost	Circuitry (A/D)	Complexi- ty	Re- sponse Time	Period- ic Tun- ing	Sensed Parame- ters	Stabil- ity	Accura- cy	PS
Artificial Bee Colony (ABC)	Expensive (E)	Digital (D)	Medium	Fast	No	V, I	Very Stable (VS)	Medium	Ye s
Ant Colony Optimiza- tion (ACO)	Afforda- ble (AF)	Digital (D)	Low	Fast	Yes	V, I	VS	Medium	Ye s
Adaptive Neuro- Fuzzy In- ference System (ANFIS)	Expensive (E)	Digital (D)	High	Fast	Yes	V, I	Stable	Medium	Ye s
Artificial Neural Network (ANN)	Expensive (E)	Digital (D)	High	Medium	Yes	V, I or G, T	Very Stable (VS)	High	Ye s
Adaptive Reference Voltage (ARV)	Inexpen- sive (IE)	Ana- log/Digital (A/D)	Low	Fast	Yes	V, I	Not Stable (NS)	Medium	No
Cuckoo Search (CS)	Very Ex- pensive (VE)	Digital (D)	Low	Fast	No	V, I	VS	High	Ye s
Constant Voltage (CV)	Inexpen- sive (IE)	Analog (A)	Low	Slow	Yes	V	NS	Low	No
Fuzzy Log- ic Control (FLC)	Afforda- ble (AF)	Digital (D)	High	Medium	Yes	V, I	VS	High	Ye s
Fractional PSO (FPSO)	Very Ex- pensive (VE)	Digital (D)	Low	Fast	Yes	V, I	VS	High	Ye s
Fuzzy Slid- ing-Mode MPPT (FSB MPPT)	Afforda- ble (AF)	Digital (D)	High	Fast	Yes	V, I	VS	High	Ye s
Genetic Algorithm (GA)	Afforda- ble (AF)	Digital (D)	High	Very Fast	No	V, I	VS	Medium	Ye s
Gated Neu- ral Tree (GNT)	Afforda- ble (AF)	Digital (D)	Very High	Fast	No	V, I	Stable	Medium	No
Grey Wolf Optimizer (GWO)	Afforda- ble (AF)	Digital (D)	Low	Medium	Yes	V	VS	High	Ye s
GWO with P&O	Afforda- ble (AF)	Digital (D)	High	Fast	Yes	V	VS	High	Ye s

Hill Climbing (HC)	Inexpensive (IE)	Digital (D)	Low	Medium	No	V, I	Stable	Medium	No
HC-ANFIS Hybrid	Affordable (AF)	Digital (D)	High	Fast	No	V, I	VS	High	Yes
Incremental Conductance (InC)	Expensive (E)	Digital (D)	Medium	Various	No	V, I	Stable	Medium	No
Improved P&O (IP&O)	Expensive (E)	Digital (D)	Medium	Medium	No	V, I	Stable	High	No
Look-Up Table Based MPPT (LTB MPPT)	Inexpensive (IE)	Digital (D)	Low	Slow	Yes	G, T or I, T	Memory-based	High	No
Open Circuit Voltage (OCV)	Inexpensive (IE)	Analog (A)	Low	Slow	Yes	V	NS	Low	No
Perturb and Observe	Inexpensive (IE)	Analog/Digital (A/D)	Low	Fast	Yes	V, I	NS	Medium	No

VIII. CONCLUSION

Four types of MPPT techniques have been evaluated in this review, sorted by nine main comparison criteria. Conventional, intelligent, optimization-based, and hybrid strategies were discussed in this case. Common photovoltaic systems perform well in situations with the same sunlight, but difficulty arises when some areas of the panel do not get enough light. Alternatively, the use of intelligent, optimization, and hybrid techniques means that the global maximum power point can be located with improved performance, though it takes more effort and is more expensive.

Regardless of the developments of other techniques, Perturb and Observe (P&O) are still the main tool used by industry because they offer simplicity and save money. Still, when it comes to quick reactions and reliable operations, intelligent optimization and hybrid techniques beat regular strategies. This work will guide researchers and engineers in choosing the right MPPT strategy for the situation they face.

REFERENCES

[1]. Park, J., Kim, H., Cho, Y., & Shin, C. (2014). Simple modeling and simulation of photovoltaic panels using MATLAB/Simulink modeling of photovoltaic module. *Advanced Science and Technology Letters, 73*, 147–155.

[2]. Odou, O. D. T., Bhandari, R., & Adamou, R. (2019). Hybrid off-grid renewable power system for sustainable rural electrification in Benin. *Re- newable Energy, 145*, 1266–1279. https://doi.org/10.1016/j.renene.2019.06.065

[3]. Bose, B. K. (2010). Global warming: Energy, en- vironmental pollution, and the impact of power electronics. *IEEE Industrial Electronics Maga- zine, 4*(1), 6–17. https://doi.org/10.1109/MIE.2010.935861

[4]. Chauhan, A., & Saini, R. P. (2014). A review on integrated renewable energy system based power generation for stand-alone applications: Configu- rations, storage options, sizing methodologies and control. *Renewable and Sustainable Energy Re- views, 38*, 99–120. https://doi.org/10.1016/j.rser.2014.05.079

[5]. Prasad, A. K., Singh, R. P., &Kafatos, M. (2006). Influence of coal based thermal power plants on aerosol optical properties in the Indo-Gangetic ba- sin. *Geophysical Research Letters, 33*(5), L05805. https://doi.org/10.1029/2005GL023801

[6]. Cheng, P.-C., Peng, B.-R., Liu, Y.-H., Cheng, Y.-S., & Huang, J.-W. (2015). Optimization of a fuzzy-logic-control-based MPPT algorithm using the particle swarm optimization technique. *Ener- gies, 8*(6), 5338–5360. https://doi.org/10.3390/en8065338

[7]. Tseng, S.-Y., & Wang, H.-Y. (2013). A photovol- taic power system using a high step-up converter for DC load applications. *Energies, 6*(2), 1068– 1100. https://doi.org/10.3390/en6021068

[8]. Natividad, L. E., &Benalcazar, P. (2023). Hybrid renewable energy systems for sustainable rural development: Perspectives and challenges in en- ergy systems modeling. *Energies, 16*(3), 1328. https://doi.org/10.3390/en16031328

[9]. Nassar, Y. F., Alsadi, S. Y., El-Khozondar, H. J., Ismail, M. S., Al-Maghalseh, M., Khatib, T., Sa'Ed, J. A., Mushtaha, M. H., &Djerafi, T. (2022). Design of an isolated renewable hybrid energy system: A case study. *Materials for Re- newable and Sustainable Energy, 11*, 225–240. https://doi.org/10.1007/s40243-022-00270-4

[10]. Miao, C., Teng, K., Wang, Y., & Jiang, L. (2020). Technoeconomic analysis on a hybrid power sys- tem for the UK household using renewable ener- gy: A case study. *Energies, 13*(12), 3231. https://doi.org/10.3390/en13123231

[11]. Sabishchenko, O., Rębilas, R., Sczygiol, N., &Urbański, M. (2020). Ukraine energy sector management using hybrid renewable

energy systems. *Energies, 13*(7), 1776. https://doi.org/10.3390/en13071776

[12]. Bubalo, M., Bašić, M., Vukadinović, D., &Grgić, I. (2023). Hybrid wind-solar power system with a battery-assisted quasi-Z-source inverter: Optimal power generation by deploying minimum sensors. *Energies, 16*(4), 1488. https://doi.org/10.3390/en16041488

[13]. AlAbri, A., AlKaaf, A., Allouyahi, M., Al Wahai- bi, A., Ahshan, R., Al Abri, R. S., & Al Abri, A. (2022). Techno-economic and environmental analysis of renewable mix hybrid energy system for sustainable electrification of Al-Dhafrat rural area in Oman. *Energies, 16*(1), 288. https://doi.org/10.3390/en16010288

[14]. Islam, M. R., Akter, H., Howlader, H. O. R., &Senjyu, T. (2022). Optimal sizing and techno- economic analysis of grid-independent hybrid en- ergy system for sustained rural electrification in developing countries: A case study in Bangladesh. *Energies, 15*(17), 6381. https://doi.org/10.3390/en15176381

[15]. Alex, Z. (2005, November 28–30). Design of an optimised PV system for a remote Himalayan vil- lage. In *Proceedings of the ANZSES*, Dunedin, New Zealand.

[16]. Van Beuzekom, I., Gibescu, M., &Slootweg, J. G. (2015, June 29–July 2). A review of multi-energy system planning and optimization tools for sus- tainable urban development. In *Proceedings of the 2015 IEEE Eindhoven PowerTech*, Eindhoven, The Netherlands, pp. 1–7. https://doi.org/10.1109/PTC.2015.7232434

[17]. Fazelpour, F., Soltani, N., & Rosen, M. A. (2014). Feasibility of satisfying electrical energy needs with hybrid systems for a medium-size hotel on Kish Island, Iran. *Energy, 73*, 856–865. https://doi.org/10.1016/j.energy.2014.06.042

[18]. Ludin, N. A., et al. (2021). Environmental impact and levelised cost of energy analysis of solar pho- tovoltaic systems in selected Asia Pacific region: A cradle-to-grave approach. *Sustainability, 13*, 396. https://doi.org/10.3390/su13010396

[19]. Rehman, S. (2020). Hybrid power systems— Sizes, efficiencies, and economics. *Energy Explo- ration & Exploitation, 39*, 3–43. https://doi.org/10.1177/0144598720931804

[20]. Zahraee, S., Assadi, M. K., &Saidur, R. (2016). Application of artificial intelligence methods for hybrid energy system optimization. *Renewable and Sustainable Energy Reviews, 66*, 617–630. https://doi.org/10.1016/j.rser.2016.08.028

[21]. Bounechba, H., Bouzid, A., Nabti, K., &Benalla, H. (2014). Comparison of perturb & observe and fuzzy logic in maximum power point tracker for PV systems. *Energy Procedia, 50*, 677–684. https://doi.org/10.1016/j.egypro.2014.06.082

[22]. Ngan, M. S., & Tan, C. W. (2011, April). A study of maximum power point tracking algorithms for stand-alone photovoltaic systems. In *2011 IEEE Applied Power Electronics Colloquium* (pp. 22– 27). IEEE.

[23]. Awad, M., et al. (2020). Performance evaluation of concentrator photovoltaic systems integrated with a new jet impingement-microchannel heat sink and heat spreader. *Solar Energy, 199*, 852– 863. https://doi.org/10.1016/j.solener.2020.03.090

[24]. Giallanza, A., Porretto, M., Puma, G. L., &Marannano, G. (2018). A sizing approach for stand-alone hybrid photovoltaic-wind-battery sys- tems: A Sicilian case study. *Journal of Cleaner Production, 199*, 817–830. https://doi.org/10.1016/j.jclepro.2018.07.214

[25]. Murphy, F., & McDonnell, K. (2017). A feasibil- ity assessment of photovoltaic power systems in Ireland; a case study for the Dublin region. *Sus- tainability, 9*, 302. https://doi.org/10.3390/su9020302

[26]. Kazem, H. A., & Khatib, T. (2013). A novel nu- merical algorithm for optimal sizing of a photo- voltaic/wind/diesel generator/battery microgrid using loss of load probability index. *International Journal of Photoenergy, 2013*, 1–8. https://doi.org/10.1155/2013/975876

[27]. Gebrehiwot, K., Mondal, A. H., Ringler, C., &Gebremeskel, A. G. (2019). Optimization and cost-benefit assessment of hybrid power systems for off-grid rural electrification in Ethiopia. *Ener- gy, 177*, 234–246. https://doi.org/10.1016/j.energy.2019.04.059

[28]. Murugaperumal, K., Srinivasn, S., & Prasad, G. S. (2019). Optimum design of hybrid renewable en- ergy system through load forecasting and different operating strategies for rural electrification. *Sus- tainable Energy Technologies and Assessments, 37*, 100613. https://doi.org/10.1016/j.seta.2019.100613

[29]. Jalal, D., & Mehdi, N. (2021). Optimization methods of MPPT parameters for PV systems: Review, classification, and comparison. *Journal of Modern Power Systems and Clean Energy, 9*, 225–236.

[30]. Nkambule, M. S., et al. (2020). Comprehensive evaluation of machine learning MPPT algorithms for a PV system under different weather condi- tions. *Journal of Electrical Engineering & Tech- nology,16*,411–427. https://doi.org/10.1007/s42835-020-00500-1

[31]. Hohm, D. P., &Ropp, M. E. (2002). Comparative study of maximum power point tracking algo- rithms. *Progress in Photovoltaics: Research and Applications,11*,47–62. https://doi.org/10.1002/pip.459

[32]. Bendib, B., Belmili, H., &Krim, F. (2015). A sur- vey of the most used MPPT methods: Conven- tional and advanced algorithms applied for photo- voltaic systems. *Renewable and Sustainable En- ergy Reviews, 45*, 637–648. https://doi.org/10.1016/j.rser.2015.02.009

[33]. Martinez Lopez, V. A., et al. (2022). Study on the effect of irradiance variability on the efficiency of the perturb-and-observe maximum power point tracking algorithm. *Energies, 15*, 7562. https://doi.org/10.3390/en15207562

[34]. Seyedmahmoudian, M., et al. (2016). State of the art artificial intelligence-based MPPT techniques for mitigating partial shading effects on PV sys- tems—A review. *Renewable and Sustainable En- ergy Reviews, 64*,435–455. https://doi.org/10.1016/j.rser.2016.06.053

[35]. Ram, J., Rajasekar, N., &Miyatake, M. (2017). Design and overview of maximum power point tracking techniques in wind and solar photovoltaic systems: A review. *Renewable and Sustainable Energy Reviews,73*, 1138–1159. https://doi.org/10.1016/j.rser.2017.01.094

[36]. da Rocha, M. V., Sampaio, L. P., & da Silva, S. O. (2020). Comparative analysis of MPPT al- gorithms based on Bat algorithm for PV systems under partial shading condition. *Sustainable En- ergy Technologies and Assessments, 40*, 100761. https://doi.org/10.1016/j.seta.2020.100761

[37]. Mao, M., et al. (2020). Classification and summa- rization of solar photovoltaic MPPT techniques: A review based on traditional and intelligent control strategies. *Energy Reports, 6*, 1312–1327. https://doi.org/10.1016/j.egyr.2020.05.009

[38]. Chen, P.-C., Liu, Y.-H., Chen, J.-H., & Luo, Y.-F. (2015). A comparative study on maximum power point tracking techniques for photovoltaic genera- tion systems operating under fast changing envi- ronments. *Solar Energy, 119*, 261–276. https://doi.org/10.1016/j.solener.2015.06.032

[39]. Subudhi, B., & Pradhan, R. (2012). A comparative study on maximum power point tracking tech- niques for photovoltaic power systems. *IEEE Transactions on Sustainable Energy, 4*, 89–98. https://doi.org/10.1109/TSTE.2012.2202294

[40]. Salas, V., Olías, E., Barrado, A., &Lázaro, A. (2006). Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems. *Solar Energy Materials and Solar Cells, 90*, 1555–1578. https://doi.org/10.1016/j.solmat.2005.10.023

[41]. Shmroukh, A. N. (2019). Thermal regulation of photovoltaic panel installed in Upper Egyptian conditions in Qena. *Thermal Science and Engi- neering Progress, 14*, 100438.

https://doi.org/10.1016/j.tsep.2019.100438
[42]. Puig, N. I. P. D. L., Acho, L., &Rodellar, J. (2018). Design and experimental implementation of a hysteresis algorithm to optimize the maxi- mum power point extracted from a photovoltaic system. *Energies, 11*, 1866. https://doi.org/10.3390/en11071866
[43]. Ahmad, R., Murtaza, A. F., & Sher, H. A. (2018). Power tracking techniques for efficient operation of photovoltaic array in solar applications—A re- view. *Renewable and Sustainable Energy Re- views, 101*, 82–102. https://doi.org/10.1016/j.rser.2018.10.014
[44]. Bollipo, R. B., Mikkili, S., &Bonthagorla, P. K. (2021). Hybrid, optimization, intelligent and clas- sical PV MPPT techniques: A review. *CSEE Journal of Power and Energy Systems, 7*, 9–33. https://doi.org/10.17775/CSEEJPES.2019.02690
[45]. Kavya, M., & Jayalalitha, S. (2020). Develop- ments in perturb and observe algorithm for maxi- mum power point tracking in photovoltaic panel: A review. *Archives of Computational Methods in Engineering, 28*, 2447–2457. https://doi.org/10.1007/s11831-020-09438-5
[46]. Motahhir, S., El Hammoumi, A., & El Ghzizal, A. (2019). The most used MPPT algorithms: Review and the suitable low-cost embedded board for each algorithm. *Journal of Cleaner Production, 246*, 118983. https://doi.org/10.1016/j.jclepro.2019.118983
[47]. Rezk, H., &Eltamaly, A. M. (2015). A comprehensive comparison of different MPPT techniques for photovoltaic systems. *Solar Energy, 112*, 1– 11. https://doi.org/10.1016/j.solener.2014.11.010
[48]. Eltawil, M. A., & Zhao, Z. (2013). MPPT tech-niques for photovoltaic applications. *Renewable and Sustainable Energy Reviews, 25*, 793–813. https://doi.org/10.1016/j.rser.2013.05.022
[49]. De Brito, M. A. G., Galotto, L., Sampaio, L. P., Melo, G. D. A. E., &Canesin, C. A. (2013). Eval- uation of the main MPPT techniques for photovol- taic applications. *IEEE Transactions on Industrial Electronics, 60*(3), 1156–1167. https://doi.org/10.1109/TIE.2012.2198036
[50]. Karami, N., Moubayed, N., &Outbib, R. (2017). General review and classification of different MPPT techniques. *Renewable and Sustainable Energy Reviews, 68*, 1–18. https://doi.org/10.1016/j.rser.2016.09.132
[51]. Elbarbary, Z. M. S., &Alranini, M. A. (2021). Review of maximum power point tracking algo- rithms of PV system. *Frontiers in Engineering and Built Environment, 1*, 68–80. https://doi.org/10.3389/fenbe.2021.00068
[52]. Verma, D., Nema, S., Shandilya, A. M., & Dash, S. K. (2016). Maximum power point tracking (MPPT) techniques: Recapitulation in solar pho- tovoltaic systems. *Renewable and Sustainable En- ergy Reviews, 54*, 1018–1034. https://doi.org/10.1016/j.rser.2015.10.068
[53]. Yadav, I., Maurya, S. K., & Gupta, G. K. (2020). A literature review on industrially accepted MPPT techniques for solar PV system. *International Journal of Electrical and Computer Engineering (IJECE), 10*(2), 2117–2127. https://doi.org/10.11591/ijece.v10i2.pp2117-2127
[54]. Li, J., Wu, Y., Ma, S., Chen, M., Zhang, B., & Jiang, B. (2022). Analysis of photovoltaic array maximum power point tracking under uniform environment and partial shading condition: A re- view. *Energy Reports, 8*, 13235–13252. https://doi.org/10.1016/j.egyr.2022.09.139
[55]. Zainudin, H. N. (2010). Comparison study of maximum power point tracker techniques for PV systems. In *Proceedings of the 14th International Middle East Power Systems Conference (MEP- CON'10)* (pp. 750–755). Cairo University, Egypt.
[56]. Tozlu, Ö. F., &Çalık, H. (2021). A review and classification of most used MPPT algorithms for photovoltaic systems. *Hittite Journal of Science and Engineering, 8*(3), 207–220. https://doi.org/10.17350/HJSE19030000235
[57]. Selvan, S., & Nair, P. (2016). A review on photo- voltaic MPPT algorithms. *International Journal of Electrical and Computer Engineering, 6*(2), 567– 582. https://doi.org/10.11591/ijece.v6i2.7884
[58]. Mousa, H. H., Youssef, A.-R., & Mohamed, E. E. (2020). State of the art perturb and observe MPPT algorithms based wind energy conversion sys- tems: A technology review. *International Journal of Electrical Power & Energy Systems, 126*, 106598. https://doi.org/10.1016/j.ijepes.2020.106598
[59]. Jiang, J.-A., Su, Y.-L., Kuo, K.-C., Wang, C.-H., Liao, M.-S., Wang, J.-C., Huang, C.-K., Chou, C.- Y., Lee, C.-H., & Shieh, J.-C. (2017). On a hybrid MPPT control scheme to improve energy harvest- ing performance of traditional two-stage inverters used in photovoltaic systems. *Renewable and Sus- tainable Energy Reviews, 69*, 1113–1128. https://doi.org/10.1016/j.rser.2016.11.227
[60]. Elgendy, M. A., Zahawi, B., & Atkinson, D. J. (2011). Assessment of perturb and observe MPPT algorithm implementation techniques for PV pumping applications. *IEEE Transactions on Sus- tainable Energy, 3*(1), 21–33. https://doi.org/10.1109/TSTE.2011.2168244
[61]. Alik, R., Jusoh, A., &Sutikno, T. (2015). A review on perturb and observe maximum power point tracking in photovoltaic system. *TELKOMNIKA (Telecommunication Computing Electronics and Control), 13*(3), 745–751. https://doi.org/10.12928/TELKOMNIKA.v13i3.1 369
[62]. Kolluru, V. R., Narne, R., &Patjoshi, R. K. (2017). Implementation of a novel P&O MPPT controller for photovoltaic system at standard test conditions. *International Journal of Applied En- gineering Research, 12*, 2017–2021.
[63]. Sera, D., Mathe, L., Kerekes, T., Spataru, S. V., & Teodorescu, R. (2013). On the perturb-and- observe and incremental conductance MPPT methods for PV systems. *IEEE Journal of Photo- voltaics, 3*(3), 1070–1078. https://doi.org/10.1109/JPHOTOV.2013.2261118
[64]. Pandey, A., & Srivastava, S. (2019). Perturb & observe MPPT technique used for PV system un- der different environmental conditions. *Interna- tional Research Journal of Engineering and Technology, 6*(6), 2829–2835.
[65]. Khodair, D., Motahhir, S., Mostafa, H. H., Shaker, A., El Munim, H. A., Abouelatta, M., & Saeed, A. (2023). Modeling and simulation of modified MPPT techniques under varying operating climatic conditions. *Energies, 16*(2), 549. https://doi.org/10.3390/en16020549
[66]. Seguel, J. L., Seleme, S. I., &Morais, L. M. F. (2022). Comparative study of buck-boost, SEPIC, Cuk and Zeta DC-DC converters using different MPPT methods for photovoltaic applications. *En- ergies,15*,7936. https://doi.org/10.3390/en15217936
[67]. [67]. Piegari, L., & Rizzo, R. (2010). Adaptive perturb and observe algorithm for photovoltaic maximum power point tracking. *IET Renewable Power Gen- eration, 4*(4), 317–328. https://doi.org/10.1049/iet-rpg.2009.0016
[68]. [68]. Jately, V., Azzopardi, B., Joshi, J., Sharma, A., & Arora, S. (2021). Experimental analysis of hill- climbing MPPT algorithms under low irradiance levels. *Renewable and Sustainable Energy Re- views,150*, 111467. https://doi.org/10.1016/j.rser.2021.111467
[69]. Noh, H.-J., Lee, D.-Y., & Hyun, D.-S. (2002). An improved MPPT converter with current compen- sation method for small scaled PV applications. In *Proceedings of the IEEE 2002 28th Annual Con- ference of the Industrial Electronics Society (IE- CON 02)* (pp. 1113–1118). Sevilla, Spain.
[70]. Leedy, A. W., Guo, L. P., &Aganah, K. A. (2012). A constant voltage MPPT method for a solar powered boost converter with DC motor load. In *Proceedings of the 2012 IEEE SoutheastCon* (pp. 1–6). Orlando, FL, USA. https://doi.org/10.1109/SECon.2012.6197044

[71]. Elgendy, M. A., Zahawi, B., & Atkinson, D. J. (2010). Comparison of directly connected and constant voltage controlled photovoltaic pumping systems. *IEEE Transactions on Sustainable Ener gy, 1*(3), 184–192. https://doi.org/10.1109/TSTE.2010.2066276

[72]. Kimball, J. W., &Krein, P. T. (2007). Digital rip- ple correlation control for photovoltaic applica- tions. In *Proceedings of the 2007 IEEE Power Electronics Specialists Conference* (pp. 1690– 1694). Orlando, FL, USA. https://doi.org/10.1109/PESC.2007.4342251

[73]. Ho, B. M. T., Chung, S.-H., & Hui, S. Y. R. (2004, February 22–26). *An integrated inverter with maximum power tracking for grid-connected PV systems*. In **Proceedings of the Nineteenth Annual IEEE Applied Power Electronics Con- ference and Exposition, APEC'04** (pp. 1559– 1565). Anaheim, CA, USA.

[74]. Salman, S., Ai, X., & Wu, Z. (2018). Design of a P-&-O algorithm based MPPT charge controller for a stand-alone 200W PV system. *Protection and Control of Modern Power Systems, 3*, 25. https://doi.org/10.1186/s41601-018-0092-7

[75]. Sarvi, M., &Azadian, A. (2021). *A comprehensive review and classified comparison of MPPT algo- rithms in PV systems*. Springer. https://doi.org/10.1007/978-3-030-67021-0

[76]. Alghuwainem, S. (1994). Matching of a DC motor to a photovoltaic generator using a step-up con- verter with a current-locked loop. *IEEE Transac- tions on Energy Conversion, 9*(1), 192–198. https://doi.org/10.1109/60.282500

[77]. Lasheen, M., Rahman, A. K. A., Abdel-Salam, M., &Ookawara, S. (2017). Adaptive reference voltage-based MPPT technique for PV applica- tions. *IET Renewable Power Generation, 11*(5), 715–722.https://doi.org/10.1049/iet- rpg.2016.0336

[78]. Tey, K. S., &Mekhilef, S. (2014). Modified in- cremental conductance MPPT algorithm to miti- gate inaccurate responses under fast-changing so- lar irradiation level. *Solar Energy, 101*, 333–342. https://doi.org/10.1016/j.solener.2014.01.036

[79]. Jiang, J.-A., Huang, T.-L., Hsiao, Y.-T., & Chen, C.-H. (2005). Maximum power tracking for pho- tovoltaic power systems. *Journal of Applied Sci- ence and Engineering, 8*(2), 147–153.

[80]. Messalti, S., Harrag, A., &Loukriz, A. (2017). A new variable step size neural networks MPPT controller: Review, simulation and hardware im- plementation. *Renewable and Sustainable Energy Reviews, 68*, 221–233. https://doi.org/10.1016/j.rser.2016.09.130

[81]. Craciunescu, D., &Fara, L. (2023). Investigation of the partial shading effect of photovoltaic panels and optimization of their performance based on high-efficiency FLC algorithm. *Energies, 16*(3), 1169. https://doi.org/10.3390/en16031169

[82]. Li, X., Wen, H., Hu, Y., & Jiang, L. (2019). A novel beta parameter based fuzzy-logic controller for photovoltaic MPPT application. *Renewable Energy,130*, 416–427.https://doi.org/10.1016/j.renene.2018.06.086

[83]. Kihal, A., Krim, F., Laib, A., Talbi, B., &Afghoul, H. (2018). An improved MPPT scheme employ- ing adaptive integral derivative sliding mode con- trol for photovoltaic systems under fast irradiation changes. *ISA Transactions, 87*, 297–306. https://doi.org/10.1016/j.isatra.2018.02.008

[84]. Kim, I.-S., Kim, M.-B., &Youn, M.-J. (2006). New maximum power point tracker using sliding- mode observer for estimation of solar array cur- rent in the grid-connected photovoltaic system. *IEEE Transactions on Industrial Electronics, 53*(4), 1027–1035. https://doi.org/10.1109/TIE.2006.878324

[85]. Miyatake, M., Inada, T., Hiratsuka, I., Zhao, H., Otsuka, H., & Nakano, M. (2004, August 14–16). *Control characteristics of a Fibonacci-search- based maximum power point tracker when a pho- tovoltaic array is partially shaded*. In **Proceed- ings of the 4th International Power Electronics and Motion Control Conference (IPEMC 2004)** (pp. 816–821). Xi'an, China.

[86]. Ramaprabha, R., Balaji, M., & Mathur, B. (2012). Maximum power point tracking of partially shad- ed solar PV system using modified Fibonacci search method with fuzzy controller. *International Journal of Electrical Power & Energy Systems, 43*(1), 754–765. https://doi.org/10.1016/j.ijepes.2012.05.014

[87]. Zhang, J.-H., Wei, X.-Y., Hu, L., & Ma, J.-G. (2019). A MPPT method based on improved Fib- onacci search photovoltaic array. *TehnickiVjesnik, 26*(1), 163–170. https://doi.org/10.17559/TV-20170327132420

[88]. Xiao, W., Dunford, W. G., Palmer, P. R., & Capel, A. (2007). Application of centered differ- entiation and steepest descent to maximum power point tracking. *IEEE Transactions on Industrial Electronics, 54*(5),2539–2549. https://doi.org/10.1109/TIE.2007.899923

[89]. Kumar, S., Kaur, T., Arora, M., & Upadhyay, S. (2019). Resource estimation and sizing optimiza- tion of PV/micro hydro-based hybrid energy sys- tem in rural area of Western Himalayan Himachal Pradesh in India. *Energy Sources, Part A: Recov- ery, Utilization, and Environmental Effects, 41*(21), 2795–2807. https://doi.org/10.1080/15567036.2018.1561653 [90]. Ishaque, K., Salam, Z., Shamsudin, A., & Amjad,

[90]. M. (2012). A direct control based maximum pow-er point tracking method for photovoltaic system under partial shading conditions using particle swarm optimization algorithm. *Applied Energy, 99*, 414–422. https://doi.org/10.1016/j.apenergy.2012.05.037 [91]. Khare, A., &Rangnekar, S. (2013). A review of particle swarm optimization and its applications in solar photovoltaic system. *Applied Soft Compu- ting, 13*(6),2997–3006. https://doi.org/10.1016/j.asoc.2012.10.009

[91]. Miyatake, M., Veerachary, M., Toriumi, F., Fujii, N., & Ko, H. (2011). Maximum power point tracking of multiple photovoltaic arrays: A PSO approach. *IEEE Transactions on Aerospace and Electronic Systems, 47*(1), 367–380. https://doi.org/10.1109/TAES.2011.5705681

[92]. Rezk, H., Fathy, A., & Abdelaziz, A. Y. (2017). A comparison of different global MPPT techniques based on meta-heuristic algorithms for photovolta- ic system subjected to partial shading conditions. *Renewable and Sustainable Energy Reviews, 74*, 377–386. https://doi.org/10.1016/j.rser.2017.02.050