A Qualitative Review of Artificial Intelligence Based MPPT Techniques

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Abstract- *Artificial Intelligence (AI) is becoming increasingly popular in many areas, including the field of maximum power point tracking (MPPT), where it is used to optimize the power output from a photovoltaic (PV) system. There are several methods for AI based MPPT, each with their own advantages and disadvantages, as well as different levels of complexity. In this article, we will discuss the most popular AI based MPPT techniques, their advantages and disadvantages, and the complexity associated with each.*

Keywords- Solar Cells, MPPT, Fuzzy logic, Particle swarm optimization (PSO), Ant Colony Optimization, Unscented Kalman filters (UKFs).

I. INTRODUCTION

To begin, it is important to understand how a solar cell works. Solar cells are devices that capture energy from sunlight and convert it into electrical energy. The amount of electrical energy they produce is determined by the amount of sunlight they are exposed to, as well as their efficiency. When the sunlight is strong and the cell is working efficiently, the MPP is at its maximum. Thus, it is important for solar cells to be able to accurately track their MPP to ensure that they are running as efficiently as possible.[1]Maximizing power point tracking (MPPT) is a technique used to maximize the power output from a photovoltaic (PV) system. Traditional MPPT techniques include fuzzy logic, perturb and observe (P&O), incremental conductance (IC), and hill climbing. These methods rely on iterative adjustment of duty cycles to achieve accurate power tracking. While these methods are effective, they are slow and require dedicated hardware. Whereas, AI based MPP tracking is a way of using artificial intelligence algorithms to accurately track and optimize the MPP of solar cells. This is done by employing various machine learning and deep learning techniques to monitor the performance of the solar cell and adjust its performance accordingly. By doing so, the solar cell can be made to run more efficiently and produce more energy. In this review, we examine the use of AI-based MPPT techniques to improve the performance of a PV system.

II. AI-BASED MPPT TECHNIQUES

AI-based MPPT techniques offer an alternative to traditional methods. These methods rely on data-driven models and use machine learning algorithms to learn the optimal duty cycle settings which result in maximum power output. AI-based MPPT techniques are faster and more accurate than traditional methods, and they can be implemented on existing PV systems with minimal modifications.

- **Advantages of AI-Based MPPT Techniques**

AI-based MPPT techniques have several advantages over traditional methods. First, they are faster and more accurate, resulting in more efficient and reliable power tracking. Second, they require minimal modifications and can be implemented on existing PV systems. Finally, as the machine learning algorithms learn the optimal duty cycle settings, the system performance can be improved over time without manual intervention. The main benefit of using AI based MPP tracking is that it can significantly improve the efficiency of solar cells. By using AI algorithms to analyze the performance of the solar cell and adjust it accordingly, the cell can achieve its maximum power output more quickly and accurately.[2] This can lead to significant cost savings and increased energy production. However, there are also some limitations to using AI based MPP tracking. For example, the algorithms used by AI based MPP tracking are often computationally intensive and require significant amounts of data to accurately track the MPP. This can be difficult and costly to obtain in some cases. In addition, AI algorithms can be difficult to implement in real-world applications due to their complexity.

- **AI Methods to Enhance Performance of Solar Power Cells**

Artificial intelligence methods can be used to enhance overall performance in scaling solar power systems, especially when powerful computer systems are used. AI can also be used to develop algorithms that can make point tracking for maximum power more efficient. Hybrid systems that use synergy of AI and other technologies are also being studied in order to lessen the environmental effect of solar photovoltaic systems.AI is used to enhance power conversion efficiency and ensure MPPT controller in PV panels and PV arrays. Traditional PV systems use charge controllers to obtain continuous maximum power but AI can help optimize the system's charge. AI also helps in tracking technologies to ensure the maximum power point under varying climatic conditions. This helps in optimizing the system's charge while ensuring that the point tracking order is met under varying ecological conditions. Theapplication of Artificial Intelligence (AI) in tracking Maximum Power Point for Solar Cell is an effective way to maximize the system's power output. AI-based MPPT systems can be used in PV systems to self-optimize power output by selecting the optimized algorithm. This helps in reducing the need for a relatively complex control circuit. The AI-based MPPT control algorithm is designed to detect and track the point of maximum power from a PV source in real time, regardless of environmental factors such as temperature or installation method. It helps optimize the system's operating point and maximize its power output with improved efficiency than other methods without requiring any user input or manual adjustments.[3]

II. DIFFERENT AI BASED MPPT TECHNIQUES

Modern maximum power point tracking (MPPT) systems use several types of artificial intelligence (AI) techniques to optimize the performance and efficiency of photovoltaic (PV) systems. The most commonly used AI techniques are fuzzy logic, neural networks, and genetic algorithms.

III. ARTIFICIAL NEURAL NETWORK

The biological neural networks in animal brains inspired the ANN or connectionist system. It is used to train and test the I-V and P-V nonlinearity relationship. ANN gathers inputs ranging from input current, input voltage, irradiance, temperature, and metrological data and constantly learns to adapt the behaviour of the solar power system for maximum power. FLC design may be simulated using ANN for more accuracy and simpler converter implementation.

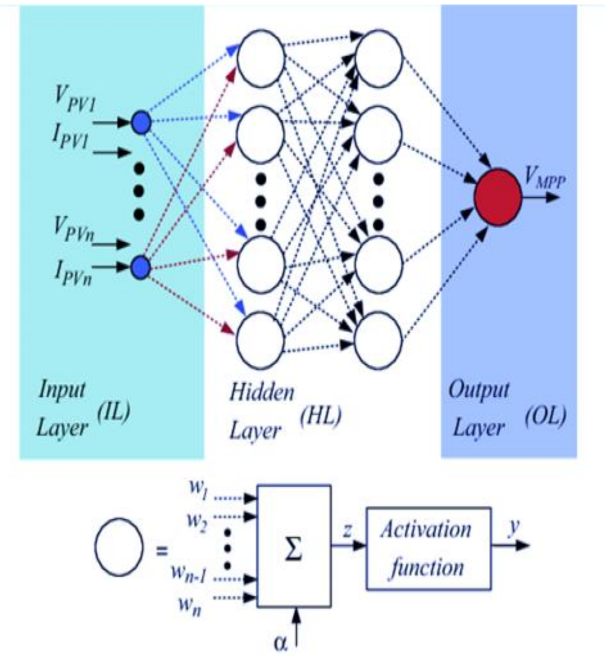

Figure1: Multilayer Feed Forward Neural Network[4]

The dataset is obtained from the simulation or hardware setup by feeding solar irradiances, temperatures, solar power system voltage or current to ANN in order to discover the relevant P_{max} or V_{max} output, as seen in the Figure below. After being transformed into training data, these data are sent into the artificial neural network (ANN) being developed. Test datasets are used to assess the trained ANN's effectiveness, with the resulting mistakes feeding back into the ANN to fine-tune the design. It may be used to supplement state estimate using sequential Monte Carlo (SMC) filtering and MPP prediction. The IC MPPT method's architecture may accommodate a state-space model for sequential MPP estimation, and the ANN model uses voltage and current or irradiance data to enhance SMC's calculation of GMPP.[5]
ANN's benefits include, among others, the ability to model non-linear relationships with high precision and to solve issues with little to no input from the user.

IV. PARTICLESWARM OPTIMIZATION (PSO)

It is a meta-heuristic algorithm based on the collective social behaviour of a group of birds or insects. It has been widely used in various fields such as engineering optimization, machine learning, and finance. In the field of maximum power point tracking (MPPT), PSO has been used to optimize the performance of solar cells by minimizing the non-linearity between the temperature and the output current of the photovoltaic system. In this process, PSO is used to find the optimal operating point for the solar cell by iteratively searching for the values of various parameters such as the bus voltage, open circuit voltage (Voc), and maximum power point (MPP).[6]

To achieve the optimal output, the algorithm first identifies the location of the MPP by calculating the gradient of the power-voltage curve. Then, the parameters of the system are adjusted according to the gradient values and the output is compared with the expected output. This process is repeated until the desired accuracy is achieved. ThePSO algorithm maintains a swarm of individuals (called particles), where each particle represents a candidate solution. Particles follow a simple behaviour: emulate the success of neighbouring particles and its own achieved successes. The position of a particle is therefore influenced by the best particle in a neighbourhood, p_{best} as well as the best solution found by all the particles in the entire population, g_{best}The particle position,χ_i ,is adjusted using where the velocity component, , represents the step size.

$$\chi_i^{t+1}=\chi_i^{t}+\nu_i^{t+1}$$

The velocity is calculated by[7]

$$\nu_i^{t+1}=\omega\nu_i^{t}+c_1 r_1.(\,p_{best},\ i-x_i^t)+c_2 r_2.(\,g_{best}-x_i^t),$$

i=1,2,….N,

whereχ_i denote the particle position for i; the velocity of the particle at i is represented byν_i ; the number of iteration is denoted by t ; the inertia weight is represented byω and r_1 and r_2 are uniformly distributed random variables within[0,1]; and the cognitive and social coefficient are, respectively, denoted by $c_1 c_2$. The best position for the storage of the ith particle that has been found so far is denoted by variable $p_{best\,,\,i}$and the storage of the best position of all the particles is represented by g_{best} . [8]

V. FUZZY LOGIC CONTROL SYSTEM

The fuzzy logic control system works by tracking the maximum power point (MPP) of the PV module. It does this by taking into account the environmental parameters such as temperature, irradiance, and voltage levels to adjust the PV module's operating voltage to ensure optimal performance. The fuzzy logic control system also takes into account the changes in the PV module's operating voltage and subsequently adjusts the current and voltage levels to maintain the MPP. The fuzzy logic control system has been developed to provide reliable and efficient power tracking, even under varying environmental conditions. It is also capable of providing a robust and reliable system by taking into account the power characteristics of the PV module. Furthermore, the fuzzy logic control system can be tuned to the specific characteristics of the PV module to ensure optimal performance under all environmental conditions.

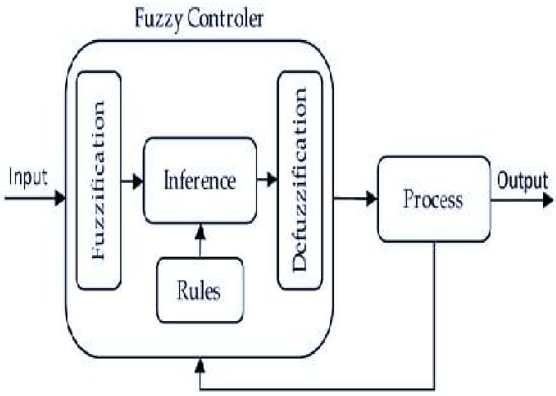

Figure 3: Block Diagram of FLC [9]

The FLC comprise in three steps fuzzification, inference rule base and defuzzification. Fig Block diagram shows these techniques. The input variable of the fuzzification but these variables are generally known as an error ‘e(k)’ and variation in error (Δe(k)). The main work of fuzzification is using membership function converts crips value to linguistics value. The triangular membership is highly popular show in fig. and table .

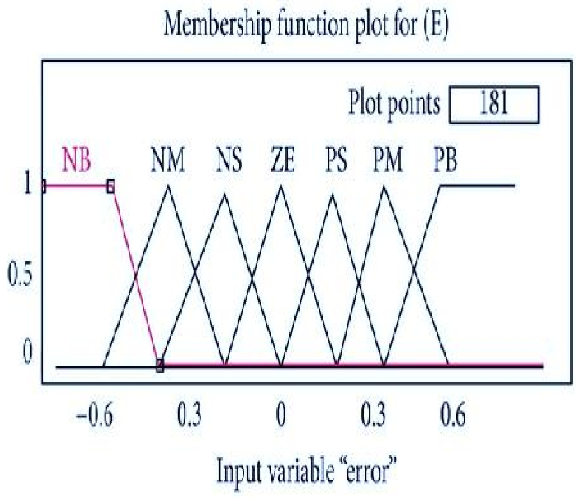

Figure 4: Membership Function [10]

Rule Table of FLC [11]

$\Delta P_p \nu \Delta I_p \nu$	**P**	**Z**	**N**
PB	PB	PB	NB
PM	PM	PM	NM
PS	PS	PS	NS

ZZ	PS	ZZ	NS
NS	NS	NS	PS
NM	NM	NM	PM
NB	NB	NB	PB

Output variables are control according to rule inference engine. Using a rule base table the membership function base inference engine applies rules. In defuzzification convert output linguistic to relevant crisp & numerical value[12] . In MPPT application input variable calculate using this equations:

$$(e(t)) = \frac{\Delta p(t)}{\Delta v(t)} = \frac{p(t)-p(t-1)}{v(t)-v(t-1)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\Delta e(t) = e(t)- e(t-1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

In FLCP(t) power value and V(t) voltage value are the operating point, respective; t is the sampling time; next step of the operation direction of the operating point define by the Δe(t), and position e(t) of the operating point in the P-V. Then, the MPP is calculated using the fuzzy rules from the above table, with the logic being "THEN Changes applied AND power increased THEN- continue the direction," which is used to describe the DC-DC converter's necessary change in operation cycle. [13]

VII. ANTCOLONY OPTIMIZATION BASED MAXIMUM POWER POINT TRACKING (MPPT)

Ant Colony Optimization based Maximum Power Point Tracking (MPPT) is a meta-heuristic approach to optimize the power output of a photovoltaic (PV) system. It is inspired by the foraging behaviour of ant colonies and allows the PV system to operate at its optimal power point (OPP) for maximum power extraction.

The main idea of the ACO based MPPT is to use an artificial ant colony to search for the global optimum of the PV system's performance. The artificial ants will search the PV system's power-voltage curve to find the OPP. To achieve this, the artificial ants are allowed to move along the power-voltage curve and adjust their movement according to their current power input and voltage output. The movement of the ants is guided by a heuristic algorithm which takes into account the current power input and voltage output of the PV system.[14]

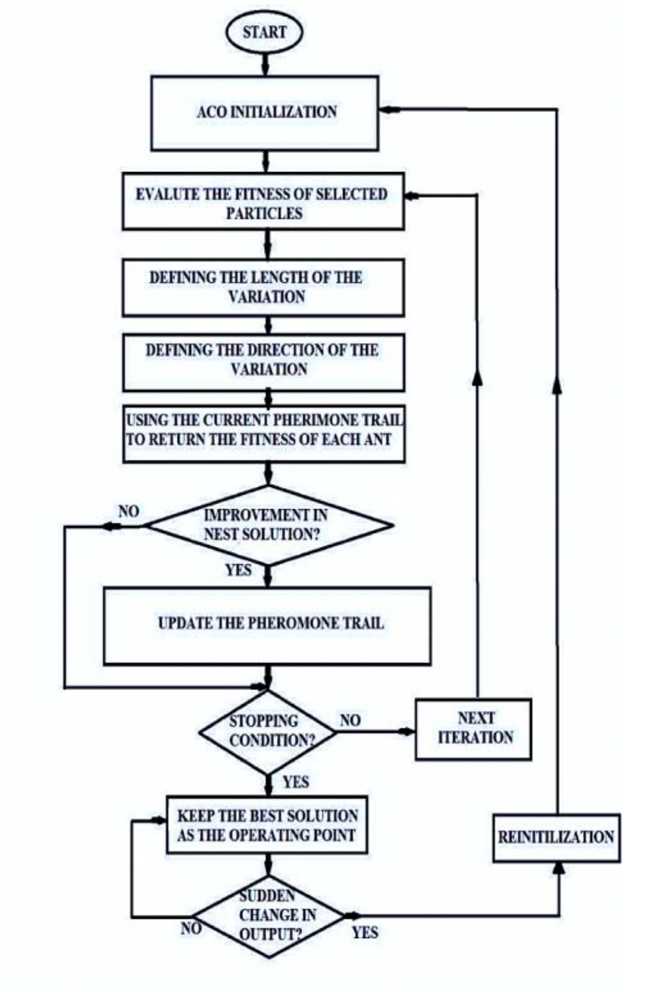

Figure 6 :ACO based MPPT flow chart [14]

The ACO-based MPPT uses a grid-based representation of the PV array's voltage at each point. Each ant's optimal fitness value, represented by the F(x) objective function, is ranked by its voltage score. The following equation displays the 1st iteration of the location matrix, assuming n ants are involved.[15]

$$X_l^i=[X_l^1,X_l^2,\ldots..X_l^N]$$

The ACO based MPPT is a reliable and efficient method for tracking the OPP of the PV system. It has been used to achieve up to 30% more power output compared to traditional MPPT algorithms. Furthermore, the ACO based MPPT algorithm is relatively easy to implement, does not require any complicated mathematical calculations, and can be implemented in any type of system. Additionally, the ACO based MPPT algorithm requires very little energy and can be deployed remotely by wireless communication.

VIII. UNSCENTED KALMAN FILTERS (UKFS)

Unscented Kalman filters (UKFs) are a powerful tool used in the Maximum Power Point Tracking (MPPT) of solar cells. UKFs have been shown to be successful in tracking the optimal power output of solar cells, and in this guide we will discuss their use and implementation. The UKF approach utilizes a set of non-linear equations to track the optimal power output of a solar cell by using statistical methods to account for noise and irregularities in the cell's output. The UKF is based on the Bayesian filtering technique, which estimates the current state of a system by using past measurements and a process model. In the UKF approach, a set of sigma points are used to represent the system's uncertainty.[16] These sigma points are generated by perturbing the system's mean state vector with a sequence of Gaussian noises. The sigma points capture the relative uncertainty of different components of the system and allow for a more accurate tracking of the MPPT of the solar cell. Once the sigma points are generated, they are propagated through the system dynamics to get the predicted state vector. The process model is then used to update the expected error covariance matrix, which is used to compute the Kalman gain and the optimal prediction of the solar cell's power output.
The UKF approach has been proven to be a successful and accurate tool for tracking the optimal power output of a solar cell.

IX. APPLICATION OF HILL CLIMBING (HC) TECHNIQUE IN SOLAR CELL MAXIMUM POWER POINT TRACKING

Solar energy is an abundant and clean renewable energy source which is receiving increasing attention from researchers due to its sustainable benefits. Maximum Power Point Tracking (MPPT) is the process of continuously optimizing the output of a photovoltaic (PV) system to capture the maximum available energy from a PV module. The application of HC technique in MPPT has been studied by several researchers due to its capability to effectively search and track the maximum power point as quickly as possible.[17]

The HC technique is a local search algorithm which is applied to find the maximum power point of a PV system by repeatedly iterating to find the next possible point with increased power output. The HC technique used in MPPT is defined as an optimization process in which the PV system is driven by a current-voltage curve and the corresponding power output is monitored. The HC technique rapidly navigates the PV system to efficiently track the maximum power point by gradually increasing the current and voltage of the system until the maximum point is reached. The HC technique is based on two principles, namely the ‘ascent’ and the ‘descent’ principle. The ascent principle is applied when the power output is increased by increasing the current and voltage, and the descent principle is applied when the power output is decreased by decreasing the current and voltage. The HC technique is based on the principle of ‘one-step-ahead search’ and it does not require any prior knowledge of the system’s PV characteristics.

X. EVOLUTIONARY ALGORITHM (EA)

Evolutionary Algorithm (EA) based Maximum Power Point Tracking (MPPT) is a method of solar power optimization that uses evolutionary algorithms to identify the optimal combination of parameters to maximize the amount of energy captured from a given solar panel. EA based MPPT can be used to identify the optimal amount of power output, given a specific solar panel, ambient temperature, and other environmental conditions. The EA based MPPT method is also beneficial in tracking changing environmental conditions, and can adjust the parameters accordingly. The application of EA based MPPT is beneficial for increasing the efficiency of any solar panel system. By using the EA based optimization approach, the system is able to identify the combination of parameters that will produce the highest amount of energy from the given solar panel. This means that the system can identify the best combination of parameters for a given solar panel, even when the environmental conditions or the solar panel itself change. The EA based MPPT approach is also advantageous for reducing the cost of solar power systems. By being able to identify the optimal combination of parameters, the overall cost of the system can be minimized, as the system will not be wasting energy. By utilizing the EA based MPPT, solar panel systems are able to make the most of their available energy, and optimize their performance.[18]

XI. COMPARING DIFFERENT AI-BASED MPPT TECHNIQUES

Modern solar installations make use of Maximum Power Point Tracking (MPPT) technology to optimize energy output from the solar array. AI-based MPPT algorithms offer a distinct advantage over traditional methods, such as the Perturb and Observe algorithm, as they are able to respond faster to fluctuations in environmental conditions. In this article, we will compare the performance of several AI-based MPPT techniques, including Fuzzy Logic, Unscented Kalman Filters, and Neural Networks, to assess their suitability for different applications.

Fuzzy Logic

Fuzzy Logic-based MPPT techniques allow for the optimization of a solar array's power output through the use of fuzzy rules. Fuzzy logic allows for the definition of a system's performance in terms of qualitative parameters, such as "low", "medium" and "high". By leveraging fuzzy logic, the power output of a solar array can be optimized by adjusting the system's operating parameters in accordance with those fuzzy rules. So, the fuzzy logic system uses a set of rules to determine the best parameters, which makes it simpler than neural network or evolutionary algorithm based approaches. The main advantage of this approach is its simplicity and cost-effectiveness. However, it is not as accurate or as fast as other AI based approaches.[19]

Unscented Kalman Filters

Unscented Kalman filters (UKF) are a type of AI-based MPPT algorithm that uses a combination of statistical and probabilistic methods to optimize power output. UKF works by calculating the expectation values of a system's parameters, then using those values to calculate optimal operating parameters. This technique is particularly useful in environments with rapidly changing environmental conditions, as UKF is able to respond quickly to sudden changes.

Hill Climbing (HC) Algorithm

The Hill Climbing (HC) algorithm is one of the simplest and most widely used AI based MPPT techniques. The main purpose of the HC algorithm is to maximize the output power of a PV system by modifying its operating point. The algorithm works by incrementally adjusting the system's operating point until it finds the point that maximizes the output power. HC algorithms are relatively easy to implement and require minimal computational resources, making them a viable solution for small-scale PV systems. The main advantage of the HC algorithm is its simplicity; however, it can also suffer from local minima, meaning that the algorithm may not always find the global maximum. Additionally, HC algorithms may take a long time to find the optimal solution if the parameters vary drastically from one iteration to the next.

Particle Swarm Optimization (PSO) Algorithm

The Particle Swarm Optimization (PSO) algorithm is another popular AI based MPPT technique. Like the HC algorithm, it is used to maximize the output power of a PV system. The main difference between the two is that PSO uses a population of points, known as particles, which move around in search of the optimal solution. Each particle is associated with a fitness value, which guides the algorithm towards the optimal solution. The main advantage of PSO is that it is relatively fast and can avoid local minima. Additionally, the algorithm does not require a large amount of computational resources, making it suitable for small-scale PV systems. The main disadvantage of PSO is that it can require a large number of particles to find the optimal solution, which can lead to high computational costs.

Neural Network Based MPPT

Neural Network based MPPT is a type of AI based MPPT technique which uses a neural network to learn the best parameters for maximum power point extraction. The neural network is trained with a large set of experimental data and can provide highly accurate results. The main advantage of this approach is its high accuracy and fast response time. However, it can also be complex, time-consuming, and expensive to build and train the neural network.

Evolutionary Algorithm Based MPPT

Evolutionary Algorithm based MPPT is another AI based MPPT technique which uses evolutionary algorithms to determine the optimal solution. This approach is simpler than Neural Network based MPPT, since evolutionary algorithms are already implemented in most programming languages. Additionally, this approach is usually more cost-effective, since it does not require the use of expensive hardware for training. However, the accuracy and response time of this approach is lower than Neural Network based MPPT.

XII. CONCLUSION

It can be concluded that the current AI-based methods have faster convergence speed, higher efficiency and better accuracy than conventional ones. Furthermore, the various AI-based MPPT algorithms in terms of oscillation, current accuracy, and fast response to changing environmental conditions when compared with the traditional methods.

Artificial intelligence-based MPPT techniques are able to achieve improved maximum possible energy from a solar cell or solar power system when compared to conventional methods. The paper provides a review of the various new methods and novel mechanisms used in artificial intelligence based MPPT techniques for efficient point tracking. Finally, it can be concluded that AI-based MPPTs can outperform conventional methods in terms of tracking accuracy, response speed and overall system efficiency.[20] The realistic MPPT approach has been identified as a better option for achieving maximum power point tracking with less time and effort. In addition, the significant instalment cost of such a system is justified by its effectiveness in life implementation. In conclusion, the different AI based MPPT techniques have different advantages and drawbacks. Neural Network based MPPT is the most accurate and fastest approach, but it is also the most complex and expensive. Evolutionary Algorithm based MPPT is simpler and more cost-effective, but is not as accurate or fast. Finally, Fuzzy Logic based MPPT is the simplest approach, but is not as accurate or as fast as other AI based approach. In order to select the most suitable AI-based MPPT technique, it is important to consider the environmental conditions of the installation and the desired performance of the system. Fuzzy logic is best suited to relatively stable environments, as the system's performance can be defined in terms of qualitative parameters. Unscented Kalman filters are ideal for rapidly changing environments, as the system is able to respond quickly to sudden changes in conditions.

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