International Journal of Computer Applications (0975 – 8887)
Volume 184 – No. 42, January 2023

Comparative Analysis of Conventional and Artificial Intelligence-based Maximum Power Point Tracking Algorithms for Solar Photovoltaic Applications

Vineeth Kumar P.K.
Department of Electronics and Communication Engineering
Sri Venkateshwara College of Engineering
Bengaluru, India

Jijesh J.J.
Department of Electronics and Communication Engineering
Sri Venkateshwara College of Engineering
Bengaluru, India

ABSTRACT
Maximum Power Point Tracking (MPPT) algorithms are utilized in solar photovoltaic systems to enhance the overall performance. Various conventional MPPT algorithms are employed in solar photovoltaic systems. Nevertheless, those algorithms are futile in the Partial Shaded condition (PSC) and impotent in identifying the maximum power point. Also, the conventional algorithms failed to bi-furcate the local and global maxima during the partial shaded condition. The impact of partial shading results in the false selection of extreme power points in solar photovoltaic sources, and the total efficiency of the PV system comes down. The researchers' advanced MPPT algorithm overcomes the conventional MPPT algorithm. This research deals with the comparative analysis of conventional MPPT algorithm with Artificial Intelligence based MPPT algorithm (AI MPPT) by considering the parameters such as speed of convergence, tracking accuracy, cost of implementation, and efficiency. Moreover, the issues and challenges of selecting an optimized algorithm are discussed in this research work. The performance parameters of MPPT are evaluated individually. The fuzzy logic-based MPPT algorithm performs better than other MPPT algorithms.

General Terms
Solar photovoltaic systems (SPV), maximum power point tracking algorithm (MPPT), partial shaded condition (PSC), artificial intelligence based MPPT algorithm (AI MPPT), fuzzy logic based MPPT (FLS MPPT).

Keywords
MPPT, ICA,HCA,ANN,FLS,FSCC.

1. INTRODUCTION
Non-conventional energy sources have a vital role in the energy sector of the globe. Over 30% of energy is derived from non-conventional sources, among all other non-conventional energy sources [1] like wind energy, tidal energy, geothermal energy, biogas power generation, and many more. Solar energy sources are much more convenient by contemplating the parameters such as modularity, noise-free operation, low operation, and maintenance cost. Also, solar energy is utilized in solar photovoltaic and thermal systems. This research paper focuses on the scope of improvement in the solar photovoltaic system. Various factors such as temperaturevariation, changes in irradiance level, Partial Shaded Condition (PSC), cost of semiconductor material, and low conversion efficiency are significant challenges for solar photovoltaic systems. Those factors are considered the foremost hurdle to operating the SPV module at Maximum Power Point (MPP). Therefore the efficiency of the solar photovoltaic module is extremely low.

It is vital that the solar array needs to operate in MPP regardless of PSC, non-linear characteristics of PV cell, and variation in temperature and irradiance. Therefore suitable MPPT algorithm is to be added to solar photovoltaic system. The solar photovoltaic system comprises of solar module, a power conditioning device, and a load. The power conditioning devices are DC-AC converters and DC-DC converters. The PWM pattern is formed using the desired algorithm as the gate to power Metal Oxide Semiconductor Field Effect Transistors (MOSFET) or power Insulated Gate Bipolar Transistors (IGBT) of the power conditioning device. The MPPT algorithm works on the maximum power transfer theorem principle. According to this theorem, when the source resistance equals the load resistance, the maximum power is transferred from source to load. Here using the MPPT algorithm, the input and load resistance of the PV module are matched so that it operates as its MPP. The representation of the solar photovoltaic system with MPPT is shown in fig 1. Here MPPT control represents a forward feed control that strenuously employs the PV panel at MPP.

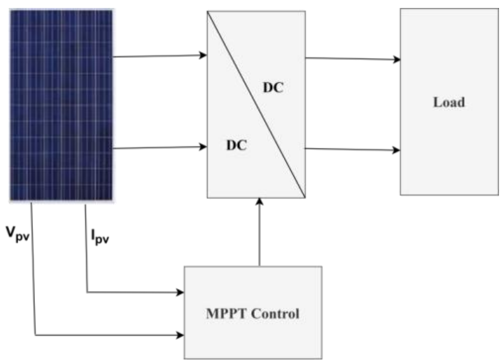

Fig 1: Schematic representation of MPPT control

The v_{pv} and i_{PV} represent the SPV panel voltage and current given to the MPPT controller. The MPPT controller generates the PWM, which is fed to the DC-DC converter's power switch, which helps the PV panel operate at an optimal point. Therefore maximum power is transferred from the source to the load. MPPT methods are broadly segmented into two: electronic tracking and mechanical tracking. The classification criteria, optimal section, and pros and cons of various MPPT algorithms are discussed in this research paper in greater detail.

Many researchers have contributed to the development of MPPT algorithms. The traditional methods of MPPT are the Incremental Conductance Algorithm (ICA), Perturb & Observe (P&O) algorithm, Fractional Open Circuit Voltage method or Constant Voltage method (CV), Hill Climbing Algorithm (HCA) and Fractional Short Circuit Current method (FSCC) [1]-[3]. Simplicity is the attractive feature of traditional MPPT, where poor performance in external environmental conditions is the major setback. Advanced methods are implemented to mitigate the setbacks of conventional MPPT. The cutting-edge techniques are operated on Artificial Intelligence (AI) and Bio-inspirational based (BI) techniques [3]-[4]. The performance of advanced methods is vastly superior, but the task implementation is complicated. This research compares the conventional MPPT and AI-based MPPT techniques by considering the performance parameters.

The research is segmented as follows: section 2 describes the taxonomy of MPPT algorithms, section 3 presents the details of conventional MPPT algorithms, section 4 presents the details of AI-based MPPT algorithms, section 5 produces the result and discussion, and section 6 concludes the research paper.

2. TAXONOMY OF MPPT ALGORITHM

Nowadays, there are various MPPT algorithms used in solar photovoltaic applications. There is no standard procedure for classifying MPPT algorithms used in solar photovoltaic systems. However, MPPT algorithms are classified according to tracking methods adopted, way of implementation, the technology used, and the electronic interface involved. The broad classification of MPPT algorithms used in the solar photovoltaic System is mentioned in Fig. 2.

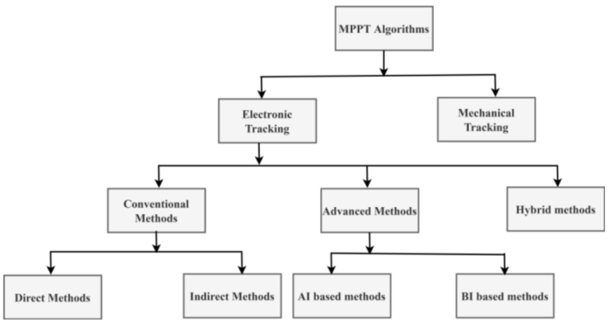

Fig. 2: Classification of MPPT algorithms in SPV systems

This research work addresses the performance comparison of conventional MPPT algorithms with AI-based MPPT algorithms. Foremost, the details of algorithms are discussed in detail. Subsequently, detailedcomparative discussions are carried out by considering the MPPT Algorithm's performance parameters.

3. CONVENTIONAL METHODS

The conventional method is the simplest compared to all other MPPT algorithms. This method is uncomplicated and easy to implement. Nevertheless, conventional MPPT algorithms are unsuitable for fast-changing environments and complex systems. The conventional methods are classified into direct methods and indirect methods. The detailed classification of conventional methods is shown in Fig. 3. In this case, direct methods sensors are required to measure electrical quantities such as current and voltage.

Conversely, no separate sensors are required for the indirect method of MPPT. The indirect measurement method works on a typical thumb rule and is less accurate than direct methods. Regarding the complexity and implementation, indirect methods are pretty convenient. Regarding the cost consideration, natural methods are expensive due to the requirement of sensors.

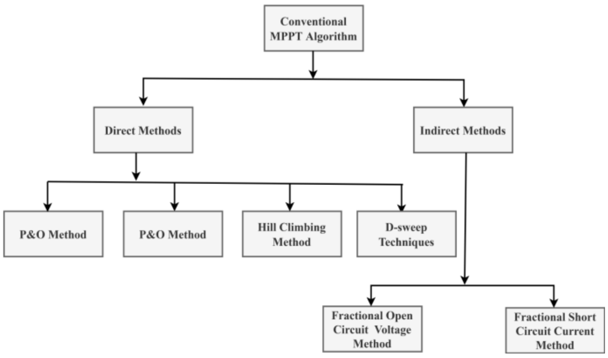

Fig. 3: Conventional MPPT algorithms in SPV systems

The P&O MPPT technique is the most linear method among the four conventional methods, and details of this algorithm are described below:

3.1 Perturb & Observe Method

Perturb & Observe method (P&O Method) [2]-[3] is a type of conventional MPPT algorithm that was developed first. In this method, the perturbation on voltage is made deliberately, and the change in the power value (dp) is checked. If power rises, the perturbation will be performed in the same direction. If the value of power decreases, perturbation is to be done in a contradictory direction [4]. In this way, searching for the maximum power point takes place. If the value of power got reduced, perturbation would be carried out in the opposite direction. This algorithm works on the principle of variation in panel output power to the change in panel voltage is zero at the MPP. According to the principle of maxima and minima in differentiation.

$$\frac{dp_{pv}}{dv_{pv}} = 0 \quad (1)$$

wheredp_{pv} is the change in PV panel output power and dv_{pv} is the change in panel voltage. The flow chart of the P&O algorithm is shown in Fig. 4. The PV panel voltage v_{pv} and i_{pv} is measured using voltage and current sensors. The monitoring process takes place continuously. Later, calculate the PV panel's available power by taking the product of PV panel voltage and PV panel current i_{pv}. Perturbation of panel voltage is performed every time and checks the panel power is examined. The reference voltage is calculated using (2):

$$V_r(n) = V_r(n-1) + \beta \, sign\left(\frac{dP_{PV}}{dV_{PV}}(n)\right) \quad (2)$$

In (2), n, n-1, n-2, n-3…., are subsequent steps mentioned as iterations. Here constant β denotes the speed of convergence that is always greater than zero. Also, the sign function in (2) is interpreted as

$$sign(y) = \begin{cases} 1, & if \ \ y > 0 \\ -1 & if \ \ y < 0 \end{cases} \quad (3)$$

The salient features of the P&O MPPT algorithm are elementary, adaptable, less complex, previous knowledge of the system is not essential, cost-effective, popular used, less required of processor, and quickly implemented using analog ICs. On the opposite hand, there are so many setbacks such as poor convergence speed under fast-changing atmospheric conditions, continuous oscillation around the MPP, a wrong section of MPP in the PSC, and substantial power losses while searching for the MPP, a lot of oscillation around MPP, poor stability and frequency response, as the power losses are high P&O gives less efficiency.

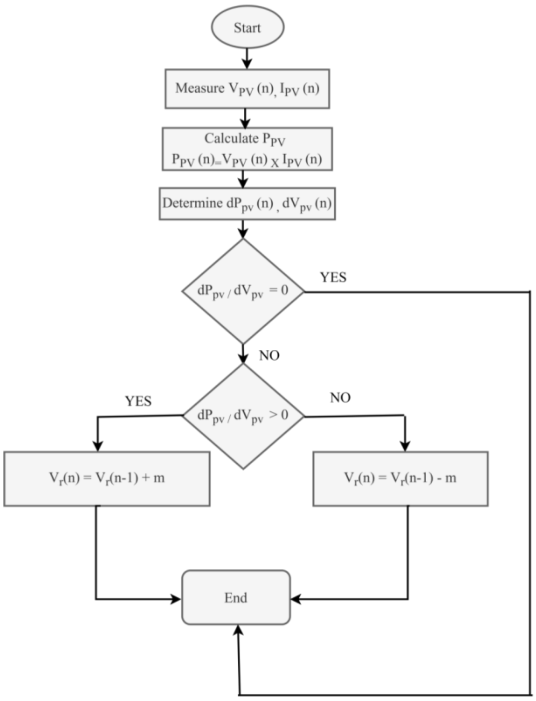

Fig4:Flow chart of P&O MPPT algorithm

There is an ambiguity in the selection of step size for this algorithm. Suppose the step size of the P&O MPPT algorithm is less [4]; an additional amount of 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. Thiscreates poor tracking accuracy and confusion. However, the step size is estimated using (4) given below:

$$C(n) = N \times \log_{10}\left(\left|\frac{dp_{pv}}{dv_{pv}}\right|\right) \quad (4)$$

where C(n) is the step size and N is the parameter depending on the PV module. Although a perfect mathematical equation is available, P&O MPPT faces the above-mentioned issue.

3.2 Incremental Conductance Algorithm

Incremental Conductance Algorithm (ICA) [4] is another conventional MPPT used in SPV systems. ICA is developed after implementing the P&O MPPT algorithm, popular next to the P&O MPPT algorithm. The operating principle of the incremental conductance algorithm is described in brief.

At the MPP, the rate of change of panel output power for change in time is considered zero. This concept is adopted from the principle of calculus. Let PV panel output power is ‘p’, Panel voltage is ‘v’, at maximum power point, mathematically.

$$\frac{dp}{dv} = 0 \quad (5)$$

The condition of maximum power is given in (5). The panel power is expressed as the product of panel current (i) and panel voltage (v). Equation (6) gives the elaborated result of differentiating Current (i) and Voltage (v) to the Voltage,

$$\frac{d}{dv}(i \times v) = i \times \frac{dv}{dv} + v \times \frac{di}{dv} = i + v\frac{di}{dv} \quad (6)$$

Applying equation (5) in (6)

$$i + v \times \frac{di}{dv} = 0$$

$$\frac{di}{dv} = -\frac{i}{v} \quad (7)$$

The condition of MPPT is given in (7). Here, the equation is known as incremental conductance and instantaneous conductance. At the MPP, incremental conductance and negative value of instantaneous conductance are equal [2]. The PV curve of the SPV module is shown in Fig. 5.

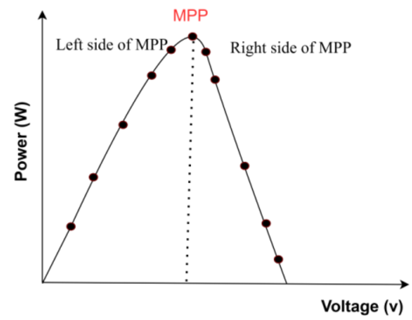

Fig 5: PV curve of solar panel

If the *dp/dv* is negative, the point locates on the left side of MPP; the Panel voltage needs to be increased by reducing the duty cycle of the power electronic converter.Conversely, if the dp/dv is positive, then the point is to the right side of MPP. So panel voltage is to be reduced by increasing the duty cycle of the power electronic converter. The algorithm completes the search once the instantaneous conductance equals incremental conductance [3]. The detailed flow chart of the ICA algorithm is shown in Fig. 6. Initially, the algorithm checks for the change in current, and the variation in voltage equals zero. If the current shift and change in voltage are equal to zero, the MPP is reached. If the voltage difference is not equal to zero, the algorithm searches whether the incremental and instantaneous conductance is equal. Suppose incremental conductance is equal to instantaneous conductance; the MPP is reached. If not, check whether the incremental conductance is more than the instantaneous conductance. If yes, the panel voltage will be increased, and the duty ratio value will be reduced to reach the MPP. Conversely, Incremental conductance is less than the negative value of instantaneous conductance, decreasing the panel voltage and increasing the duty ratio of the power converter. Suppose the change in current is more significant than zero, the panel voltage needs to be increased, and the value of the duty cycle is reduced to reach the MPP. If the variation in current is less than zero, panel voltage is to be reduced; the parallel duty cycle of the converter will be increased to achieve the MPP. The main advantages of ICA algorithms are as follows: No oscillations around the MPP similar to the P&O MPPT algorithm. The ICA algorithm manifests better stability during the fast change in atmospheric conditions. It offers better tracking speed and accuracy compared to the P&O MPPT algorithm. Also, the noise rejection is improved and not necessary for additional filter requirements in the case of the P&O MPPT algorithm.

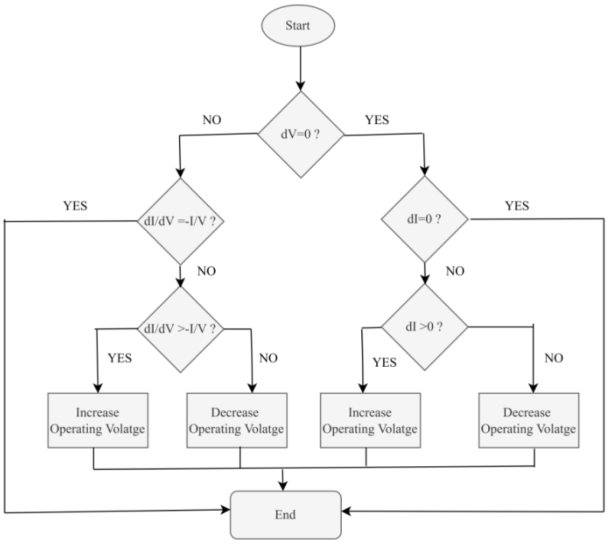

Fig 6: Flow chart of incremental conductance algorithm

$\frac{dP_{pv}}{dV_{pv}} > 0 \Rightarrow D = D + \Delta D$ 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). ICA shows poor performance in PSC. However, in contrast 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 are introduced.

3.3 Hill Climbing Algorithm

The Hill Climbing Algorithm (HCA) is a conventional MPPT algorithm. The working principle of HCA is the perturbation of the duty ratio of the power converter and observing the variation in power, and it is similar to the P&O MPPT algorithm. The difference between the P&O MPPT and HCA [5]-[6] is that in the P&O MPPT algorithm, perturbation of Panel voltage takes place. In contrast, perturbation of the duty cycle is done in the case of the HCA. First, the perturbation of the duty ratio is made intentionally, and check the change in power value (dp). If power is increasing, the perturbation is done in the same direction. If the value of power decreases, perturbation is to be performed in the opposite direction. In this way, searching for the maximum power point takes place. If the power value got reduced, perturbation would be carried out in the opposite direction, similar to that of the P&O MPPT algorithm. PV panel voltage and current are measured using suitable sensors. The duty ratio (D) of the power electronic converter (buck-boost) type is expressed in (8)

$$\frac{V_0}{V_{in}} = \frac{D}{1-D} \quad (8)$$

In (8), 'D' represents the duty ratio of the DC-DC buck-boost converter, (V_0) indicates the output voltage, and (V_{in}) is the input voltage. The converter operates in boost mode if the duty cycle exceeds 50%, whereas the converter operates in buck mode if the duty ratio is less than 50%. However, the HCA works based on perturbation in the duty cycle. The flow chart of the HCA is shown in Fig. 7. In case of the operating point is the exact position of MPP, the condition is expressed using (9). The HCA is simple, like the P&O algorithm, and a complex processor is not required, unlike the incremental conductance algorithm.

$$\frac{dp_{pv}}{dv_{pv}} = 0 \Rightarrow D = D \ and \ \Delta D = 0 \quad (9)$$

Suppose the operating point is at the left side of MPP; the condition is denoted by using (10)

$$\frac{dP_{pv}}{dV_{pv}} < 0 \Rightarrow D = D - \Delta D \quad (10)$$

Suppose the operating point is at the right side of MPP; the condition is denoted as (11)

(11)

HCA is another subset of the P&O MPPT algorithm. However, the main drawbacks are oscillation around MPP, misjudgment during fast-changing atmospheric conditions, and poor performance during PSC. Also, the accuracy of sensors depends on the implementation of this algorithm. However, the HCA is admissible in the situation where P&O is incorporated.

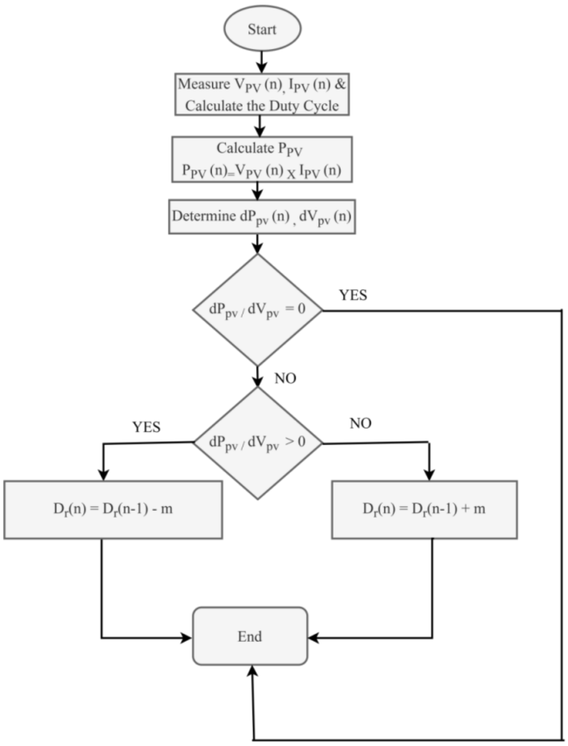

Fig 7: Flow chart of HCA MPPT technique

3.4 Constant Voltage Method

The Constant Voltage MPPT (CV) method is indirect [4]-[5]. To operate this algorithm, previous knowledge of the system, such as open circuit voltage, irradiance, and temperature, is necessary. CV method is also known as thefractional open circuit voltage method. The maximum voltage (V_{mpp}) corresponding to maximum power (P_m) is calculated using the mathematical expression (12)

$$V_{mpp} = K_v \times V_{oc} \quad (12)$$

The open circuit voltage (V_{oc}) is calculated by disconnecting the PV module from the load terminals.

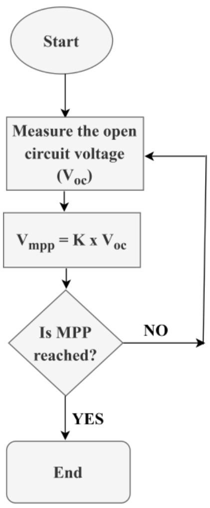

Fig 8: Constant Voltage Method

The value of constant (K_v) varies from 0.73 to 0.8. The algorithm of the constant voltage MPPT technique is shown in Fig. 8. According to this method, PV Panel must disconnect from the load and measure the (V_{oc}) using a moving coil voltmeter. Reconnect the load, and estimate the maximum voltage (V_{mpp}) corresponding to maximum power (P_m) by using (12). This method is a failure in fast-changing environmental conditions. The value of constant (K_v) directly depends on (V_{mpp}) to a maximum power point. Except for simplicity, the constant voltage MPPT technique gives poor tracking accuracy and speed. Also, this method does not differentiate between normal and fast-changing atmospheric conditions.

The discontinuation of the PV panel from the load is needed for the measurement of (V_{oc}) in a specific interval, and this procedure leads to a discontinuity of operation and power loss. This method is interpreted as an offline method of MPPT.

3.5 Fractional Short Circuit Current MPPT Methods

The Fractional Short Circuit Current MPPT (FSCC) method [7] is an indirect method similar to the CV method. This algorithm requires prior knowledge of the system, such as short circuit current, irradiance, and temperature. Initially, the PV panel's short circuit current (I_{sc}) is measured by shorting the positive and negative terminals. A moving coil ammeter is a connected series to the shorted terminals for measuring short circuit current. Clamp-on meters are adapted to calculate short circuit current for solar arrays. The maximum current corresponding to MPP is determined using (13):

$$I_{mpp} = K' \times I_{sc} \quad (13)$$

(K') varies in the range of 0.78 to 0.92 for normal conditions. It is selected based on the solar data of a particular territory. The main pros of this method are simplicity and no complicated calculations. Also, no requirements of complex signal-processing devices are required. The flow chart of FSCC MPPT is shown in Fig. 9.

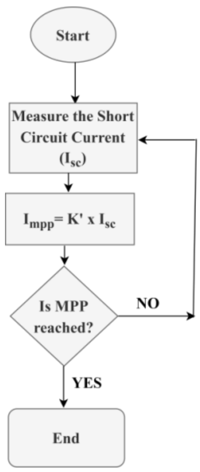

Fig 9: FSCC method

The FSCC technique is also an offline method of MPPT. The operation of the PV system needs to be interrupted while performing the FSCC method. Also, this technique is not suitable for a fast-changing environment. The dynamic performance of this algorithm is poor compared to direct MPPT methods.

4. ARTIFICIAL INTELLIGENCE BASED MPPT TECHNIQUES

Artificial intelligence-based MPPT techniques (AI MPPT) are known as soft computing methods [4]-[5]. These methods are introduced to overcome the significant setbacks of conventional MPPT algorithms. Advanced MPPT algorithm is divided into two, such as AI-based and BI-based MPPT algorithms. This research article focuses on the implementation procedure, the suitability of algorithms in SPV systems, and the pros and cons of AI MPPT techniques. The artificial intelligence-based MPPT techniques are divided into two: ANN-based MPPT algorithm and Fuzzy logic-based MPPT algorithm [8].

The demerits of conventional algorithms, such as poor performance in rapidly changing atmospheric conditions, failure in partial shaded conditions, and low tracking speed, can be mitigated using an artificial intelligence-based MPPT algorithm. The former knowledge on PV characteristics, solar irradiance level, latitude, longitude, and temperature variations will be available. Systematic data collection is required before implementing the AI-based MPPT algorithm. There are two AI-based techniques: artificial neural networks based on MPPT and fuzzy logic based on the MPPT algorithm. The technical details of both methods are described below:

4.1 ANN based MPPT algorithm

An artificial Neural Network (ANN) [9] is analogous to the human brain, which is typically a software-based technology. The human brain is made up of several neurons that are interconnected with each other. The signal transmission in the human brain takes place with the help of neurons. The signal transmission speed depends on how the neurons are connected in the human brain. The human brain is the best example of a neural network. Here dendrites of a neuron are compared with inputs; the cell body is equivalent to the processor, the synaptic is similar to the link, and the axon signifies theoutput. A neural network is a closed-loop system comprised of several processing units that operate in parallel and can utilize experimental knowledge. The artificial neural network shall consist of three major segments: nodes, links, and numeric weight. The fundamental building block of the neural network is called nodes. The neurons receive information from neighboring neurons, undergo activation states proportional to the inputs, and send one output signal to another. The general representation of the ANN technique is shown in Fig. 10.

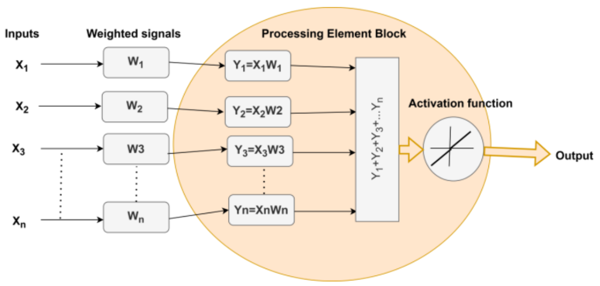

Fig 10: General block diagram of Artificial Neural network

The inputs are multiplied with a weighted signal and sent to the processing units. The desired output is obtained from the processing unit based on the manipulation, and the corresponding function is generated. There are three main segments in AI-based algorithms: input layers, hidden layers, and output layers. In the case of implementing MPPT, the input variable of the AI network is considered the input variable of the AI network, such as (V_{oc}),(I_{SC}), irradiance, and temperature. The algorithm's training belongs to the hidden layer, and PWM output is obtained at the output layer. The training of solar data and manipulations occurs at the hidden layer. The neural network diagram for PWM generation corresponding to Maximum Power is shown in Fig. 11.

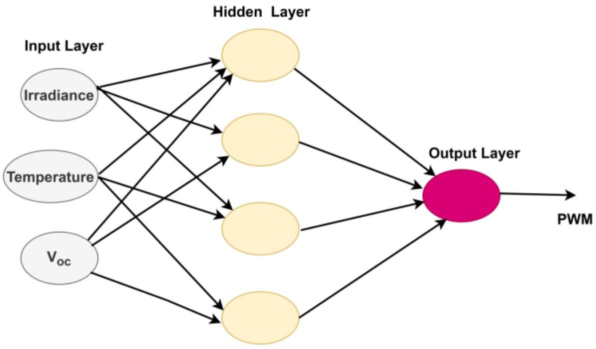

Fig 11: MPPT algorithm using AI technique

The specifications of PV panels, such as (V_{oc}),(I_{sc}) solar irradiance, and temperature, are given at the input. In Fig. 11, only three parameters are shown as input. The manipulation takes place at the hidden layer. A weighted signal multiplies with each input. The sum of manipulated out gives the output from the output layer. In this context, the output is PWM corresponding to maximum power point. Certain adjustments must be made at the hidden layer to obtain optimized MPP. Training in data set is essential in AI-based MPPT. The advantages of the AI-based MPPT technique are as follows: no current and voltage sensors are required, unlike the conventional MPPT algorithm; there is no oscillation around the MPP; higher tracking accuracy compared to the P&O MPPT algorithm, and suitable for fast-changing atmospheric conditions, no additional hardware required and accurate. Conversely, the algorithm cannot operate without deep knowledge of the data sets, fails in case of improper training of data sets, skilled persons are essential for implementing the AI-based MPPT algorithm, and there is no standard procedure for implementing this algorithm.

4.2 Fuzzy logic based MPPT algorithm

There are three components in Fuzzy Logic-based Systems (FLS) [10]-[11]. They are the fuzzification unit, interface engine, and defuzzification unit. The inputs are x1n and x2n, respectively. The fuzzification converts input signals into certain gains is called linguistic gain. The decision-making is done in the Interface engine. The Defuzzification unit converts the output of the interfacing unit (fragile value) to the real-time signal for the physical plant. The block diagram of the FLS MPPT algorithm is shown in Fig. 12.

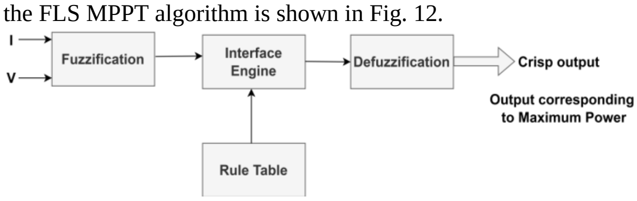

Fig 12: Fuzzy logic based MPPT Algorithm

The SPV panel current and voltage are given to the fuzzification unit. Here, fuzzification units convert current and voltage to a linguistic value. The logic works in the interface engine. For example, loops and IF-THEN statements work in the interface engine. There is a certain rule base added to the interface engine. The interface engine produces the desired output based on the rule base. The output of the interface engine is a fragile value. The fragile value is converted into a physical variable using a defuzzification unit. In this case, the output of the defuzzification unit is the maximum power corresponding to MPP. The main advantages are: no complex processor requirements, knowledge of solar data is not essential, and suitability for fast-changing atmospheric conditions. The FLS MPPT [12] is ideal for variable temperature and irradiance conditions. Studies found that there are a few oscillations around MPP. Also, the performance of this algorithm depends on the rule base and interface engine. An adaptive fuzzy logic is developed to mitigate the issues of FLS MPPT.

5. RESULTS AND DISCUSSION

There is no standard procedure to estimate the performance of the MPPT algorithm. However, the performance parameters such as complexity, robustness, efficiency, tracking speed, cost of implementation, oscillation around MPP, periodic tuning, and convergence speed can be considered before choosing a suitable algorithm. Five tables, such as tables 1, 2, 3, 4, and 5, compare the performance of conventional and AI-based MPPT techniques. Table 1 compares the conventional and advanced MPPT algorithms based on sensor requirements, mode of operation, and ripple rate.

TABLE 1: COMPARISON OF MPPT ON SENSOR REQUIREMENT& MODE OF OPERATION

Sl. No	MPPT Techniques		Sensors requirements	Mode of operation	Ripple Rate
1	Conventional MPPT	P&O	I & V sensors	online	1.02
2		ICA	I & V sensors	online	1.02
3		HCA	I & V sensors	online	1.27
4		CV	V sensor	offline	10.81
5		FSCC	I sensor	offline	5.26
6	AI based MPPT	ANN	I & V sensors	offline	0.25
7		FLS	I & V sensors	offline	0.25

The AI-based MPPT techniques are offline methods that need current and voltage sensors. In conventional MPPT techniques, except for CV and FSCC, all other methods are online. Except for CV and FSCC, all other methods require current and voltage sensors. Fig. 13 differentiates the ripple rate of conventional and AI-based MPPT algorithms.

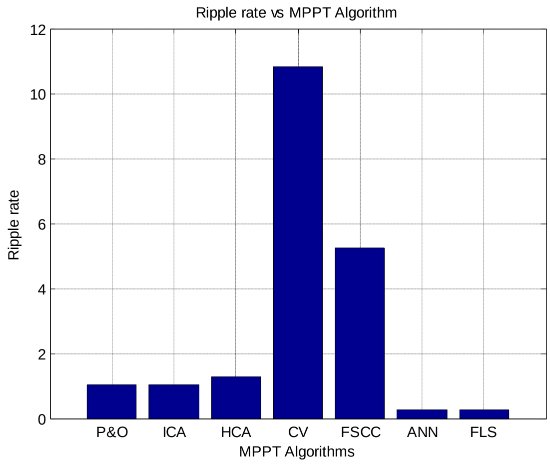

Fig. 13. Ripple rate of MPPT algorithms.

The ripple rate is not desirable for good MPPT algorithms, i.e., for an efficient algorithm, the ripple rate should be as minimum as possible. In this comparative analysis, the CV method has the highest ripple rate, whereas AI-based MPPT shows a desirable lower ripple rate. The current and voltage sensors are selected based on the MPPT technique used. Table 2 depicts the differentiation of MPPT based on efficiency and tracking accuracy.

TABLE 2: COMPARISON OF MPPT ON EFFICIENCY AND TRACKING ACCURACY

Sl. No	MPPT Techniques		Efficiency	Tracking Accuracy	Response Time (s)
1	Conventional MPPT	P&O	86%	Less accurate	0.05
2		ICA	92%	More accurate	0.06
3		HCA	87%	Less accurate	0.15
4		CV	90%	Least accurate	0.02
5		FSCC	90%	Least accurate	0.02
6	AI based MPPT	ANN	93%	More accurate	0.006
7		FLS	94%	More accurate	0.005

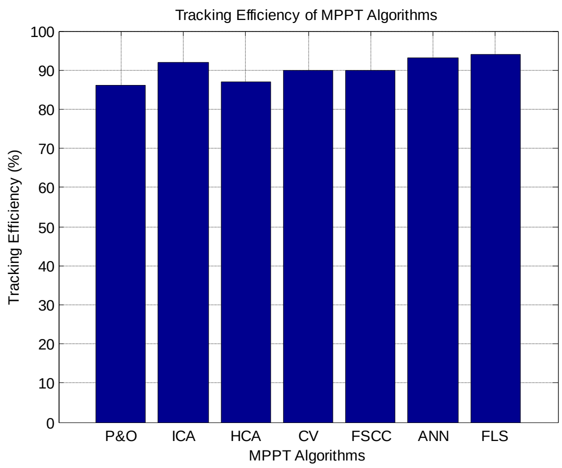

Fig14:Tracking efficiency of MPPT Algorithms

The ICA shows the highest efficiency (92%) [9] Among conventional MPPTs, and the results are more accurate. Fig. 14 shows the graph of the tracking efficiency of MPPT algorithms. The tracking accuracy and efficiency are comparatively less in the P&O & HCA algorithm.

AI-based MPPT shows high accuracy in tracking compared to the conventional MPPT algorithm. In AI-based MPPT, FLS delivers better performance than ANN.AI-based techniques show quicker response, whereas the HCA algorithm shows a longer response time (0.15 seconds). The response time of various MPPT algorithms depicts in Fig. 15. It is observed that ANN and FLS methods have less time response.

Table 3 details the MPPT algorithm's comparison based on the convergence speed and oscillation around MPP.

TABLE 3: COMPARISON OF MPPT ON SPEED OF CONVERGENCE & OSCILLATION AROUND MPP

Sl. No	MPPT Techniques		Speed of convergence (s)	Oscillation around MPP
1	Conventional MPPT	P&O	0.047	57%
2		ICA	0.01	19%
3		HCA	0.027	37%
4		CV	0.020	Nil
5		FSCC	0.020	Nil
6	AI based MPPT	ANN	0.001	Nil
7		FLS	0.001	Nil

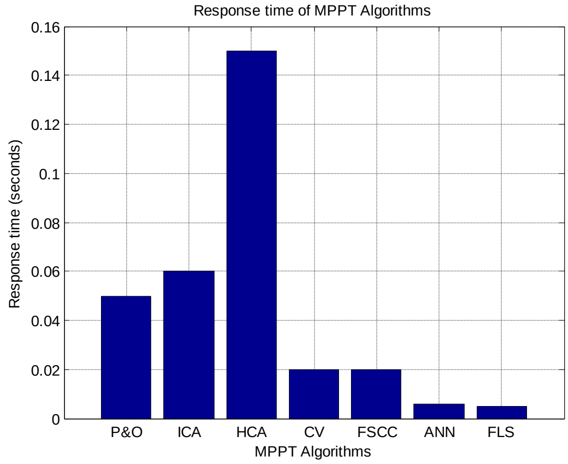

Fig15: Response time of MPPT algorithms

Compared to conventional MPPT, the convergence speed is high in AI-based MPPT. There is no oscillation around MPP in the case of AI-based MPPT, CV, and FSCC methods [14]-[15]. The P&O and HCA are not preferred in a fast-changing environment [13]. Fig. 16 depicts the comparison of conventional and AI-based MPPT algorithms based on the speed of convergence.

The complexity of implementation and cost are the essential criteria from the developer's point of view. In this regard, Table 4 compares the MPPT algorithm's performance based on the implementation's cost and complexity.

The ICA is costly and complicated among conventional MPPT algorithms. P&O is the simple and cost-effective online MPPT method. It is observed that CV and FSCC are the cheapest offline MPPT methods [14]. AI-based MPPTs are costly and complex. The researchers are trying to reduce the complexity of AI-based MPPT and make it cost-effective. Table 5 compares the MPPT algorithm based on robustness, the need for frequent tuning, and the requirement of prior knowledge of the system.

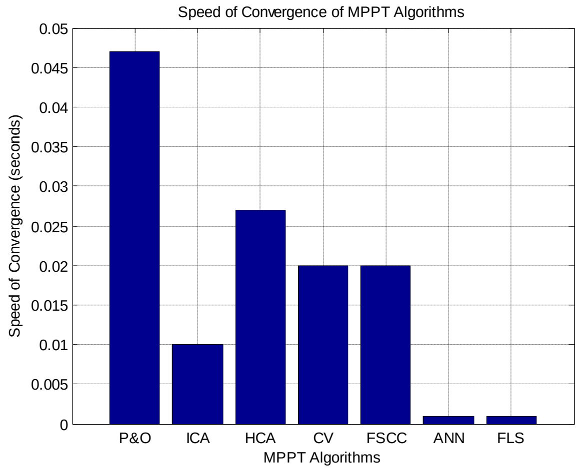

Fig16: Speed of convergence of MPPT algorithms

TABLE 4: COMPARISON OF MPPT ON COST & COMPLEXITY OF IMPLEMENTATION

Sl. No	MPPT Techniques		Cost	Complexity
1	Conventional MPPT	P&O	Low	Less
2		ICA	High	Medium
3		HCA	Low	Less
4		CV	Low	Less
5		FSCC	Low	Less
6	AI based MPPT	ANN	High	High
7		FLS	High	High

TABLE 5: COMPARISON OF MPPT ON ROBUSTNESS & REQUIREMENT OF TUNING & PRIOR KNOWLEDGE

Sl. No	MPPT Techniques		Robustness	Tuning	Prior Knowledge
1	Conventional MPPT	P&O	Less	No	Not required
2		ICA	Medium	No	Not required
3		HCA	Less	No	Not required
4		CV	Less	Yes	Required
5		FSCC	Less	Yes	Required
6	AI based MPPT	ANN	High	Yes	Required
7		FLS	High	Yes	Required

The AI methods are robust and not affected by external disturbances. Perhaps, P&O is highly subjected to the variation of external conditions such as temperature, irradiance, and partial shading. An external factor quickly affects offline methods such as CV and FSCC. The developer must choose AI-based MPPT if there is a substantial environmental variation. The conventional method, such as P&O, ICA, and HC, does not require regular tuning to reach MPP, where periodic tuning is unavoidable for AI-based MPPT, CV, and FSCC [15]. Moreover, prior knowledge of the system, such as panel specifications and solar data, is needed to implement AI-based MPPT.

While selecting an optimized MPPT technique, ranking must be done according to the performance parameters such as cost of implementation, the algorithm's complexity, speed of convergence, and overall efficiency. The advanced methods are expensive, whereas the conventional methods, such as P&O, INC, and HC, are reasonable; constant voltage and current practices are the cheapest among all other methods. The AI-based MPPT techniques are complex, whereas the conventional method, such as INC, is moderate in complexity. However, the conventional techniques, such as P&O, HC, constant voltage, and constant current, are minor and complex. Even conventional MPPT algorithm, such as INC, offers medium tracking speed.

Nevertheless, P&O and HC are showing poor tracking speed. The performance efficiency of INC and advanced methods are high; conventional methods such as P&O and HC show moderate efficiency. However, the CV and FSCC techniques offer the least efficiency. If the PV system wants to implement in a fast-changing environment, AI-based MPPT is an optimized solution. There are pros and cons to conventional MPPT and advanced MPPT. Hybrid MPPT [14]-[18] is a solution to implement an ideal solution. The researcher has to focus on the implementation of the hybrid MPPT algorithm.

The classification of the MPPT algorithm used in the solar photovoltaic system is discussed in this paper. The MPPT algorithms are classified according to conventional and advanced methods. Also, we compared the MPPT algorithms based on convergence speed, implementation complexity, cost, and efficiency. It is concluded that if the user focuses on high efficiency and tracking rate for the algorithm, it is better to choose AI-based MPPT algorithms. Nevertheless, regarding the cost consideration, P&O, HC constant voltage, and constant current methods are the favorable choice. INC algorithm is one of the best options among conventional MPPT algorithms. AI-based MPPT algorithm is appropriate in the rapidly changing environment rather than conventional MPPT Algorithms [18]-[20]. More research and development are required in the AI-based MPPT to adopt all types of SPV systems and make them practically feasible. The MPPT technique is chosen based on user needs and environmental conditions.

6. CONCLUSION

The classification of the MPPT algorithm used in the solar photovoltaic system is discussed in this paper. The MPPT algorithms are classified according to conventional and advanced methods. Also, we compared the MPPT algorithms based on convergence speed, implementation complexity, cost, and efficiency. It is concluded that if the user focuses on high efficiency and tracking rate for the algorithm, it is better to choose AI-based MPPT algorithms. Nevertheless, regarding the cost consideration, P&O, HC constant voltage, and constant current methods are the favorable choice. INC algorithm is one of the best options among conventional MPPT algorithms. AI-based MPPT algorithm is appropriate in the rapidly changing environment rather than conventional MPPT algorithms. More research and development are required in the AI-based MPPT to adopt all types of SPV systems and make them practically feasible. The MPPT technique is chosen based on user needs and environmental conditions.

7. ACKNOWLEDGEMENT

The authors thank the management and principal of Sri Venkateshwara College of Engineering (SVCE), Bangalore, India, for encouraging and completing the review paper on comparing conventional and artificial intelligence-based MPPT algorithms.

8. REFERENCES

[1] NovieAyubWindarko, MuhammadNizarHabibi, BambangSumantriet al., "A new MPPT algorithm for photovoltaic power generation under uniform and partial shading conditions", *MDPI journal of Energies*, vol. 14, no.2, pp.1-22, January 2021.

[2] Ali M Eltamaly, and Almoataz Y. Abdelaziz "*Modern maximum power point tracking techniques for photovoltaic energy system*,1st edition, *Green Energy and Technology*, 2020.

[3] Hamdan, AmiraMaghraby et al, "Random search optimization algorithm based control of supercapacitor integrated with solar photovoltaic system under climate conditions", *International Journal of Renewable Energy Research*,vol.12, no.2, pp.611-622, June 2022.

[4] Ali OmarBaba, GuangyuLiu et al, "Classification and evaluation review of maximum point tracking methods"*Journal of Sustainable Future*, vol.2, no.2, pp.1-29, April 2020.

[5] Haider A Mohammed-Kazim et al, "Efficient maximum power point tracking based on reweighted zero-attracting variable stepsize for grid interfaced photovoltaic systems", *Journal of Computers and Electrical Engineering*, vol.85, no.106672, pp.1-17, April 2020.

[6] M Mansoor, A F Mirza, and Q Ling, "Harris hawk optimization-based MPPT control for PV system under partial shading conditions", *Journal of cleaner production*, vol.274,no.122857,pp.1-19, 2020.

[7] S Lyden, Harry Galligan, and MdEnamulHaque "A hybrid simulated annealing and perturb and observe maximum power point tracking methods",*IEEE system Journal*, vol.15, no.3, pp.4325-4333, September 2021.

[8] PitchaiPandiyan, SubramaniSaravanan, NatarajanPrabaharanet al, " Implementation of Different MPPT Techniques in Solar PV Tree Under Partial Shading Conditions", *MDPI Journal of Sustainability*,vol.13,no.13, pp.1-22, June 2021.

[9] Suraj S, Jijesh J.J, and SarunSoman, "Analysis of Dual Phase Dual Stage Boost Converter for Photovoltaic Applications", *International Journal on Advanced Science, Engineering and Information Technology*, vol. 10, no.3, pp.920-928, 2020.

[10] Moacyr A G de Brito, Leonardo P Sampaio ,Luigi G Jr, Guilhereme A e Meloet al, " Comparative Analysis of

MPPT Techniques for PV Applications", in *proc*. of *International conference on clean electrical power*, 2011, doi: 10.1109/ICCEP.2011.6036361.

[11] Mohammed Aslam Husain, AbuTariq, SalmanHameed et al, "Comparitive Assessment of Maximum Power Point Tracking Procedures for Photovoltaic Systems",*Journal of Green Energy & Environment*, vol.2, no. 1, pp.5-17, January 2017.

[12] MuralidharKilli, and SusovanSamanta "An Adaptive Voltage Sensor based MPPT for Photovoltaic System with SEPIC Converter Including Steady State and Drift Analysis", *IEEE transaction on Industrial Electronics*,vol. 62, no.12, pp. 7609-7619, July 2015.

[13] Jose Miguel Riquelme –Dominguez ,and Sergio Martinez "Systematic Evaluation of Photovoltaic MPPT Algorithms using State-Space Models Under Different Dynamic Test Procedures", *IEEE Power and Energy Society Section*, vol.10, no. 21690842, pp. 45772-45783, May 2022.

[14] Claude BertinNzoundjaet al., "A comprehensive Analysis of MPPT Algorithms to optimal power extraction of a PV Panel", *Journal of Solar Energy Research*, vol.4, no.3, pp. 172-179, 2019.

[15] S.M.Sousa, L.S Gusman, T.A.S Lopes et al, "MPPT algorithm in single loop current-mode control applied to dc–dc converters with input current source characteristics", *International Journal of Electrical Power & Energy System*, vol.138, no. 107909, June 2022.

[16] AhmedSamirEldessouky et al, "MPPT based on a novel load segmentations structure for PV applications", *Ain Shams Engineering Journal*, vol.1, no. 101937, August 2022.

[17] Mustafa EnginBaşoğlu, "Comprehensive review on distributed maximum power point tracking: Submodule level and module level MPPT strategies", *Solar Energy*, vol. 241, pp. 85-108, July 2022.

[18] Vijay Laxmi Mishra et al, "A critical review on advanced reconfigured models and metaheuristics-based MPPT to address complex shadings of solar array", *Energy Conversion and Management*, vol. 269, no. 116099, October 2022.

[19] P K Vineeth Kumar and Manjunath K, "Analysis, Design, Implementation for control of Non-inverted Zeta converter using Incremental Conductance MPPT Algorithm for SPV Applications", in *proc*. of *International Conference on Inventive Systems and Control*,2017, DOI: 10.1109/ICISC.2017.8068662.

[20] Vineeth Kumar P K and Manjunath K, "A Comparitive Analysis of MPPT Algorithms for Solar Photovoltaic Systems to Improve the Tracking Accuracy", in *proc*. *International Conference on Control, Power, Communication and Computing Technologies*, March 2018, DOI: 10.1109/ICCPCCT.2018.8574336.