Maximum Power Point Tracking Achievements and Challenges in Photovoltaic Systems: Review

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Abstract— **The ever-increasing demand for electrical energy in recent decades has necessitated the exploration of alternative energy sources, one of which is solar energy. The most practical means of utilizing solar energy is through the use of a Photovoltaic (PV) system. Nevertheless, the energy harvested by PV modules is constrained by low conversion efficiency, nonlinearity, and susceptibility to weather conditions, such as temperature and irradiance levels. To address these limitations, Maximum Power Point Tracking (MPPT) techniques have been developed to optimize the output of PV systems under specific circumstances. This academic article provides an in-depth analysis of the most widely used MPPT techniques, utilizing both traditional and soft computing methods. The article discusses the fundamental principles and practical applications of these techniques, as well as the challenges associated with MPPT, such as coping with rapidly changing irradiance and partial shading scenarios.**

Keywords—maximum power point tracking (MPPT); Photovoltaic (PV); partial shading; fast irradiance.

I. INTRODUCTION

In recent decades, there has been a significant increase for electricity demand, driven by factors such as population growth, modern lifestyle demands, and the acceleration of the industrial revolution. This surge in demand has been accompanied by a rapid rise in the consumption of fossil fuels, which has raised concerns about resource depletion and environmental pollution. Furthermore, the issue of oil scarcity has been further compounded by global climate change [1]. In response to these challenges, researchers and global communities alike have been exploring alternative sources of energy. Solar energy has emerged as a promising option to supplement other renewable energy sources like wind, rain, tides, waves, and geothermal heat, thereby reducing our reliance on fossil fuels. Solar energy offers a host of benefits, including its cleanliness, sustainability, and suitability as an energy source. By mitigating environmental impact and global warming that caused by the utilizing fossil fuels, the adoption of clean energy sources like solar energy can help to reduce CO_2 emissions and promote a healthier planet [2].

Photovoltaic technology is one of the best ways to benefit from solar energy and convert sunlight to electrical energy by using solar cells which is called the PV effect. The name photovoltaic comes from the process of converting sunlight (photons) directly into electricity (voltage). In recent times, many countries have adopted the use of photovoltaic systems in various sectors as a convenient solution to meet their electricity demands. However, these systems have limited efficiency and entail high initial installation costs. To address these issues, considerable efforts are being made to enhance photovoltaic technology, with the aim of increasing efficiency and reducing costs. Some improvements had developed by scientists such as installation controllers and sensors for the PV system to track the sun continuously and orient a solar panel with the movement of the sun for concentrating the light on the solar cell. However, photovoltaic systems as known still have two problems: the first problem is the low efficiency of energy conversion the PV module. The second problem is the amount of energy which is converted from photons to voltaic by solar cell changes depending on weather conditions like varying temperatures and irradiance amount [3]. The study shows that solar panel converts 35-45% of energy falling into electrical energy, and thus it becomes necessary to use another technique to succeed in dealing with the cost problem and low efficiency of the photovoltaic system[4].

The photovoltaic module's I-V and P-V output power curves are non-linear and have a single point of maximum value called maximum power point (MPP) curve. To achieve optimal efficiency, scientists and researchers have developed a solution to keep tracking the MPP and establish operate point of the photovoltaic (PV) system. However, tracking the MPP can be difficult due to weather variations and changes in loads. There are two categories of techniques proposed to effectively track the MPP in PV system modelling. The first category is based on conventional approaches, such as the fractional open circuit method [5], the short circuit current method [6]. Perturbative & observe method [7], and incremental conductance method [8]. The conventional techniques are easy to implement, cheap and most widely used in commercial products. The second category is based on the soft computing approach, for instance the fuzzy logic control technique [9], the artificial neural network method [10], particle swarm optimisation method [11], ant-colony optimisation method [12] and differential evolution method [13].

Soft computing techniques are complex structures but have more efficient and fast response better than conventional techniques. However, partial shading and fast-changing irradiance conditions still challenge facing maximum power point tracking techniques. There are numerous academic publications regarding MPPT, making it difficult to keep track of their differences and implementation. According to the literature, there are approximately 40 different techniques for tracking MPP.

Some techniques are similar in their operating principles. This paper focuses on the latest and most commonly used techniques for MPPT and addresses the challenges of partial shading and rapidly changing irradiance, which present difficulties for MPPT techniques in photovoltaic systems [14].

II. CONCEPT OF MPPT

The photovoltaic module's output characteristics exhibit nonlinearity in both I-V and P-V curves, which means that the maximum power output corresponds to a single point at the knee of the curve where current and voltage reach their maximum values. However, the changing of temperature and irradiance levels can influence this point. Figure 1 and Figure 2 demonstrate the I-V and P-V curves under uniform and varied irradiance, respectively. To ensure maximum efficiency, it's necessary to keep track of the varying maximum power points and establish the corresponding MPP to the operating point of the PV system. This is achieved through a process called the maximum power point tracking, which is performed by the use of an electronic subsystem known as the maximum power point tracker (MPPT) system.

The MPPT controller is typically situated between the load and the photovoltaic module, as shown in Figure 3. Its function is to monitor both voltage and current of the PV module and extract the maximum value under specific conditions, as well as to match the photovoltaic system with the load. The MPPT subsystem's sole purpose is to identify the location of the maximum point. Afterwards, a DC-DC converter takes a DC input from the photovoltaic module and converts the current and voltage to AC. It then converts them back to DC, which matches the load based on the MPP to maintain the photovoltaic system's maximum efficiency. To date, photovoltaic efficiency depends on PV module, converter/inverter and MPPT technique efficiencies. Not easily improving the PV module and converter/inverter, because they depend on the available hardware, at variance the MPPT techniques, easy to improve them. Furthermore, several MPPT techniques have been reported in different works. A comparison among many different MPPT techniques has been presented in [15].

III. CONVENTIONAL MPPT TECHNIQUES

A. Fractional open circuit voltage technique (FOCVT).

The FOCVT is a simple and efficient approach for tracking the MPP, as it requires minimal parameter input and is easy to implement. This methodology is based on the concept of the highest power point output that can be located by maintaining the PV module's operating voltage (Vpv) within a range of 72% to 78% of the opening circuit voltage (Voc) under consistent conditions of weather [16]. The technique involves regulating the corresponding operating voltage of the PV cell to match a reference voltage (Vref) to keep the operating power point run close to MPP, although it may not always be exactly at MPP. The voltage reference is determined using Equation (1).

$$Vref = (0.72 - 0.78) \times Voc \qquad (1)$$

The PV module is temporarily isolated from the load and the Voc is measured, after that the reference voltage V_{ref} is determined from Eq. (1), and then the converter duty cycle is regulated to make the reference voltage of the PV module equal to the operating voltage, in order to obtain the operating point close to the maximum power point. This technique is easy to implement but the accuracy is low given the periodical shutdown of the converter to measure V_{oc}.

This algorithm is employed for tracking MPP, as illustrated in Figure 4. This approach disregards the effects of temperature and irradiance.
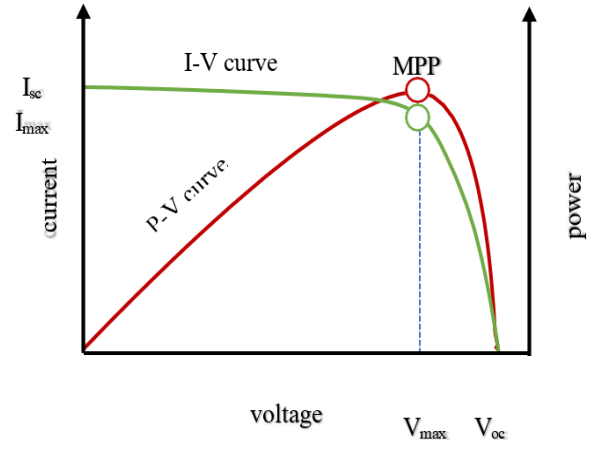

Fig. 1.   I-V and P-V curves of PV module under uniform irradiance.
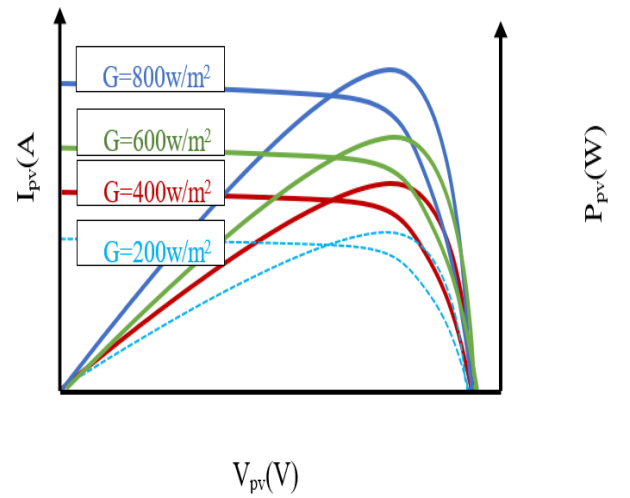

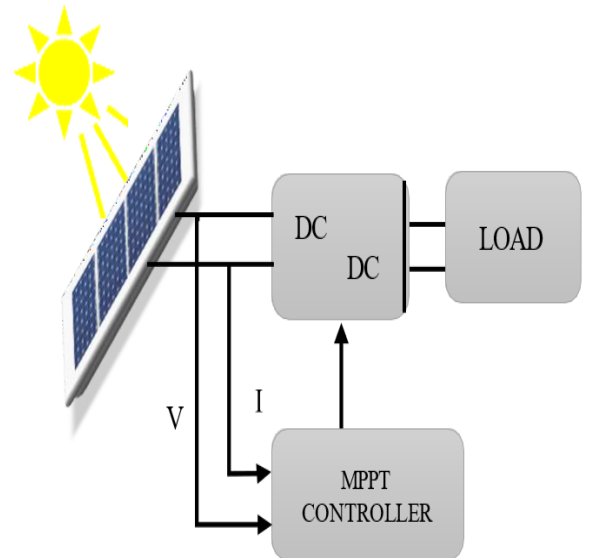Fig. 2.   I-V and P-V curves under various irradiance.

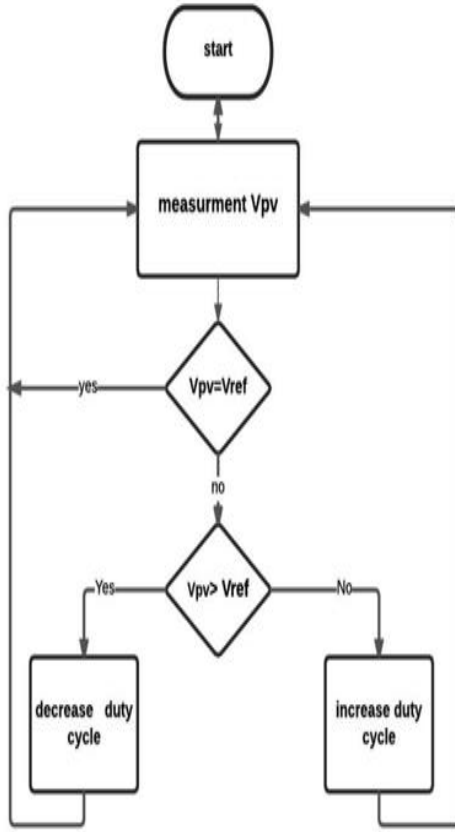Fig. 3.   Structure of photovoltaic system with MPPT controller.

Fig. 4.   Flowchart of FOCVT algorithm.

B. The Fractional short circuit current method.

This method is an alternative approach to tracking the MPP, which is comparable with the fractional open circuit voltage process. However, the key difference is that fractional short circuit current technique operates at a fixed current, while fractional open circuit voltage technique runs at a constant voltage. Identifying the MPP involves detecting the operational current of the PV module within the range of 78% to 92% of the short-circuit current Isc. In order to maintain the PV system's operational point near the MPP, it is crucial to set and regulate the operational current of the PV module to the reference current Iref as determined by Equation (2).

$$I_{ref} = (0.78 - 0.92) \, X \, I_{sc} \tag{2}$$

Firstly, we measure the short current Isc, and afterwards the reference current (Iref) is then calculated. After this, the duty cycle of the converter is then adjusted to ensure that operational current Ipv is equivalent to the reference current Iref. By following this procedure, the operational point of the PV system remains in the vicinity of the MPP. This process is repeated at regular intervals to track the MPP.

C. The Perturb & Observe (P&O) method.

This technique is a widely known technique used for tracking maximum power point in a photovoltaic (PV) system. The P&O method involves making small changes to the operating point of the system by perturbing both voltage and current in a certain direction, using a constant-sized perturbation. The control algorithm then compares the power value before and after the perturbation. If the power value

increases, it indicates that the operating power is moving towards the MPP. In such cases, these algorithms continue to perturb in the equivalent direction and by the same step size. However, if output power value after perturbation reduces, this denotes that the operating point is stepping away from the MPP, and algorithm governors the reverse perturbation direction with the identical step size. This process is repeated continuously to track the MPP. This procedure is repeated periodically until any changes occur in the weather. Figure 5 illustrates a flowchart of the P&O technique. There are two ways to implement the perturbation, are perturbation based on the direct duty cycle and perturbation based on the reference current/voltage[17]. Equation (3) is the general Equation of the perturbing & observed method.

$$x(k + 1)Tp + Sign \, (P(K) - P(K - 1))Tp \tag{3}$$

where x is the variable being perturbed either duty cycle or reference current or voltage, T_p is a period of perturbation, dx is the amplitude of perturbation and P_{pv} is the output power of the PV module.

One drawback of the perturb and observe technique is that the module voltage/current is perturbed in every cycle of MPPT, even when the MPP is reached. As a result, the oscillation of the operating point around the ideal MPP persists, causing power loss in the PV system. Figure 6 illustrates the swinging operating point around the MPP. In addition, the P&O technique suffers from misjudgment to track maximum power point fast-changing irradiance condition because the output curve of the PV module is not only a single curve, but some other curves depend on changing irradiance. This means that there are several MPPs, for each curve is one MPP[18].
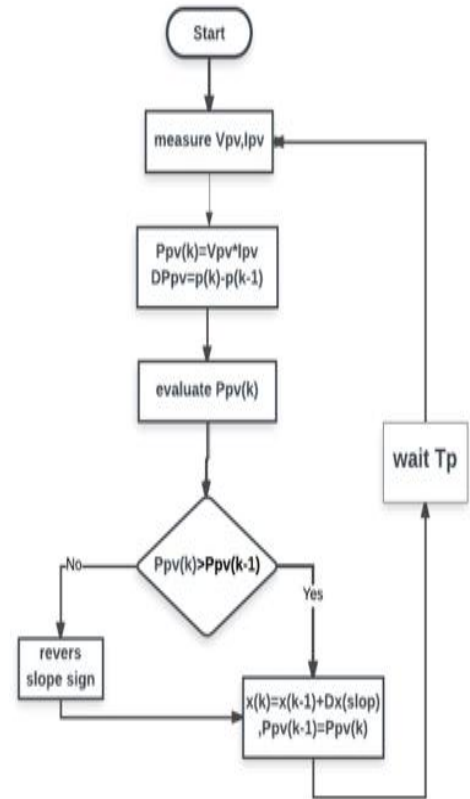

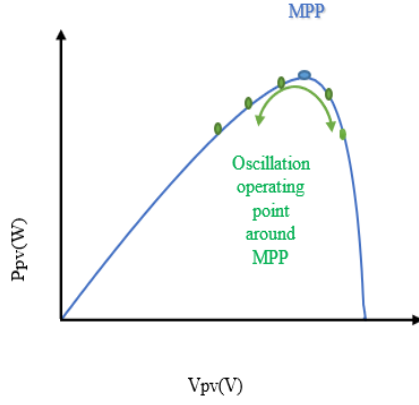Fig. 5.   Flowchart of P&O techniques.

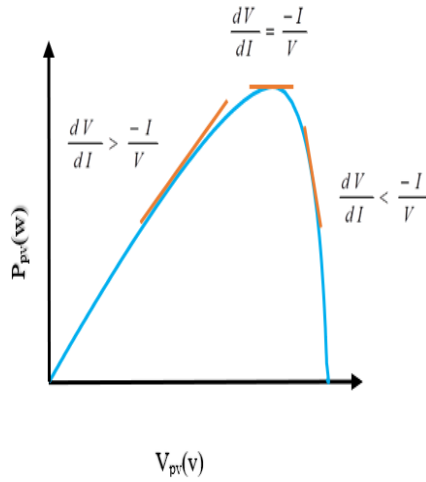Fig. 6. Oscillation operating point during P&O operation.

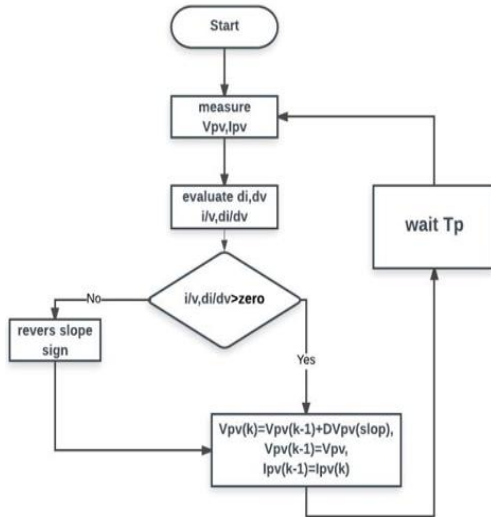Fig. 7. P-V curve characteristic of Incremental conductance.

Fig. 8. flowchart of Incremental conductance method.

A. Incremental conductance technique.

This technique is another significant method used to determine photovoltaic PV system operating point in relation to the MPP. This technique was developed to address the limitation of the perturb and observe (P&O) technique. This incremental conductance technique relies on the principle that

the MPP is reached when the derivative of the power equation with respect to voltage Eq.(4) equals zero.

$$\frac{dP}{dV} = \frac{d(I \times V)}{dV} = 0 \qquad (4)$$

Equation (4) can be expressed as the following Equation.

$$\frac{dI}{dV} = -\frac{I}{V} \qquad (5)$$

Based on the fact of Eq. (5), algorithm control compares incremental conductance value dI/dV with conductance value I/V with, to know the location of operating point. The incremental conductance technique involves determining the location of maximum power point (MPP) constructed on whether the incremental conductance value is equal to, greater than, or less than the minus conductance value. When the incremental conductance value is equivalent to the negative conductance value, the operating point is at the MPP. If the incremental conductance value surpasses the negative conductance value, then the operational point is positioned to the right of the MPP, and if the incremental conductance value is less than the minus conductance value, the operating point is to the left of the MPP [19]. Figure 7 shows the characteristics of the P-V curve for the incremental conductance technique.

Comparable to P&O technique, algorithm control applies perturbation using either a duty ratio perturbation or a feedback voltage perturbation and monitors the relationship between the conductance and incremental conductance. Based on this observation, the control decides whether to either increase or decrease perturbation, as well as to determine the next perturbation's direction, it can either be in the same direction or reversed direction, until the MPP is reached. Then, the control stops the perturbation and the PV system remains operating at the MPP till a change in irradiance changes the location of the MPP. In such a case, the perturbation and observation process is resumed to determine whether the operating point is left or right of the MPP, and the control perturbs again to find a new MPP. This process of adjusting the perturbation and its direction is repeated until the operational point aligns with the MPP once more. Figure 8. shows a flowchart of the incremental conductance method. Equation (6) is repeated to sense a condition in Eq.(5).

$$x(k+1)Tp = x(k)Tp = sign\left(\frac{I}{V}\right) + \left(\frac{dI}{dV}\right) \times dx \qquad (6)$$

where x is the perturbed variable, T_p is a period of perturb, dx is the amplitude of perturbation and P_{pv} is the output power of the PV module.

IV. SOFT COMPUTING MPPT TECHNIQUES

A. The Fuzzy logic control (FLC) technique.

FLC MPPT is a common implementation of fuzzy logic control in modern microcontrollers for monitoring MPP. The output of the MPPT controller is evaluated and managed using fuzzy logic principles in this approach. FLC is advantageous because it can handle non-linear systems, works with approximate inputs, and doesn't necessitate a precise mathematical model. See Figure 9 for an overview of the three main building blocks that make up the FLC system: fuzzification, inference engine, and defuzzification.
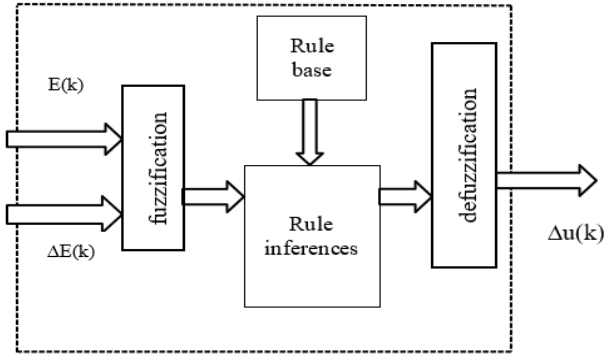
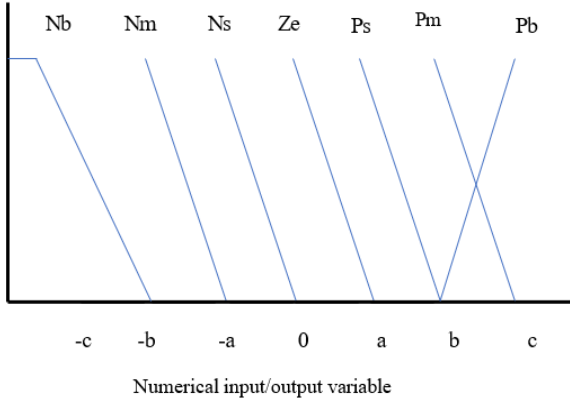Fig. 9.   The basic structure of fuzzy logic control.

Fig. 10. membership function of input and output of FLC.

1) Fuzzification

Using a membership function that defines the extent of membership in one of several fuzzy subsets, the input values are first transformed into a linguistic variable in the first step of the FLC process, known as "fuzzification." The designer's skill determines the number of fuzzy subsets used, but typically seven triangular subsets are employed: positive big (PB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), and positive medium (PM) (PB). As can be seen in Figure 10, these membership functions have a visual representation.

1) Inference engine

The rules are applied to the fuzzy sets generated in the preceding fuzzification stage, which is followed by the inference engine, the second part of the FLC process. Here, the system determines the significance of each linguistic variable in the rule inferences and saves that information in the rule table. An FLC rule base with seven triangular membership functions is shown in Table 1.

2) Defuzzification

Defuzzification, the last step in FLC, transforms the linguistic variables into the membership functions' actual output values. In most cases, an FLC will have two inputs and a single output, and it will be used in an MPPT setup. The error (E) and the variation in error (E) at sampled times k, defined by equations 7 and 8, are used as input variables in FLC for MPPT.

$$E(k) = \frac{p(k)-p(k-1)}{V(k)-V(k-1)} \qquad (7)$$

$$\Delta E(k) = E(k) - E(k-1) \qquad (8)$$

The fuzzy logic control (FLC) method utilizes Equations 7 and 8 to define the input variables, which are power (P) and voltage (V) of PV module. The FLC system's output is the duty cycle (u) of DC/DC converter, which can be modified to fine-tune operating point of PV system. The membership functions from Table 1 are used to define the input variables. If error (E) is classified as a positive big (PB) and the change in error (DE) is classified as zero (ZE) according to rule base presented in Table (1), the FLC system's output will be PB. If operating point is distant from the MPP, the controller will increase the duty cycle to bring it closer to the MPP.

B. Artificial neural network technique.

These algorithms are an effective method for monitoring the maximum power point of PV systems. These algorithms are built using principles of biological neural networks, which emulate the way the human brain processes information. The ANN is highly adept at complex calculations and can be trained to solve problems, making it an ideal choice for dealing with non-linear systems. Figure 11 shows the usual architecture of an artificial neural network (ANN) comprises of three layers: an input layer, a hidden layer, and an output layer. The irradiance, temperature, and open- and short-circuit currents of the solar module are some of the input parameters used by ANN in MPPT applications. The ANN's inputs can consist of any combination of these variables. The converter's output parameter is a reference signal used to determine the MPP and is typically the device's voltage, current, or duty cycle. The weight values of the connections between neurons in an ANN are chosen arbitrarily during its initial training process. When the ANN has been trained extensively, these weight values are fixed, allowing it to reliably monitor the PV system's MPP. The time required to train an ANN can range from a few days to several months or even years. During this time, the neural network's inputs and outputs are monitored for trends in order to improve its efficiency. An important drawback of using ANN for MPPT is that different PV modules can have different characteristics, so the ANN must be individually trained for each module. Furthermore, a PV module's characteristics can shift over time due to weather, necessitating frequent retraining of the neural network to guarantee precise MPPT. Tracking accuracy is algorithmically determined in the hidden layer. Increasing the number of nodes in the hidden layer can improve tracking accuracy, but it can also increase computational time and slow down tracking in some situations. Reducing the total number of nodes, on the other hand, can speed up computations but may compromise accuracy [20].
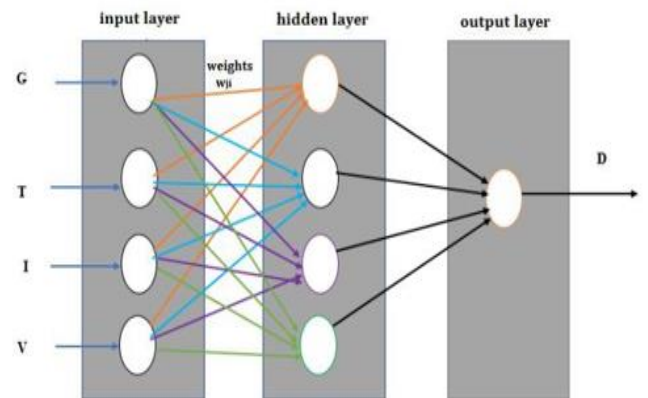

Fig. 11. ANN structure with three layers.

TABLE I. RULES-BASED THE FUZZY LOGIC CONTROLLER OF MPPT

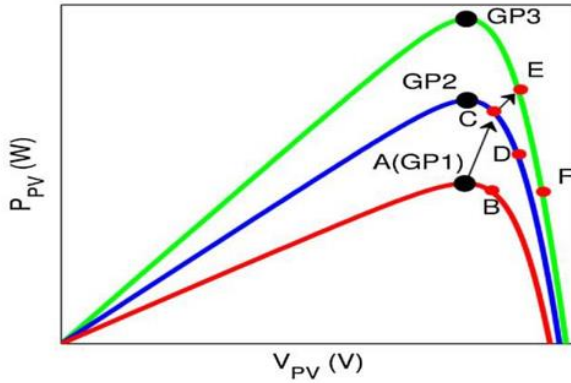| Error (E)	Change Error (CE)						
	PB	PM	PS	ZE	NS	NM	NB
PB	PB	PB	PB	PB	PM	PS	ZE
PM	PB	PB	PB	PM	PS	ZE	NS
PS	PB	PB	PM	PS	ZE	NS	NM
ZE	PB	PM	PS	ZE	NS	NM	NB
NS	PM	PS	ZE	NS	NM	NB	NB
NM	PS	ZE	NS	NM	NB	NB	NB
NB	ZE	NS	NM	NB	NB	NB	NB

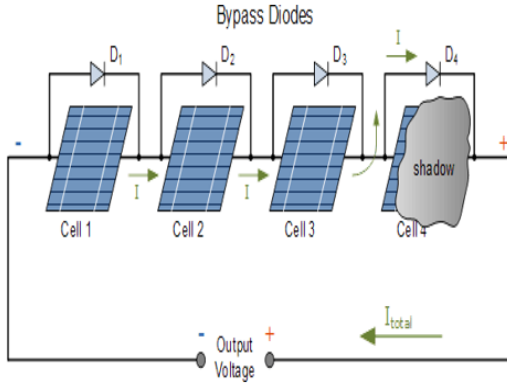Fig. 12. P-V curve of PV module under changing irradiance [21].
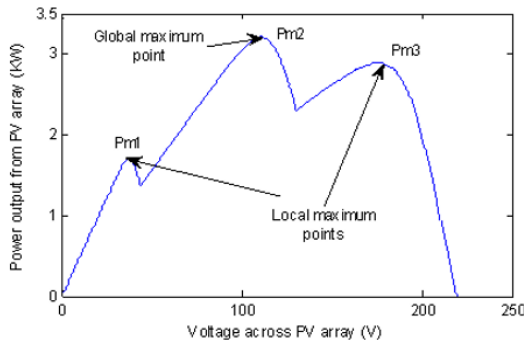

Fig. 13. one cell under partial shading.

Fig. 14. The P-V curve of PV module under partial shading.

V. CHALLENGES FACING MPPT TECHNIQUES

Both partial shading and rapid environmental change present significant difficulties for maximum power point tracking methods. When only a section of a solar panel is covered by shadow, we talk about partial shading. Because of this, it can be challenging for MPPT methods to precisely follow the MPP. When the amount of solar irradiance or temperature suddenly changes, the MPP can change just as rapidly. To keep power output at a maximum throughout these shifts, MPPT methods need to be flexible.

VI. FAST-CHANGING IRRADIANCE CONDITION SOLUTIONS.

Since there is only one maximum power point (MPP) that can be easily detected, MPPT control algorithms perform well when the irradiance is uniform and changes slowly. However, when there are sudden shifts in irradiance, traditional MPPT methods have trouble keeping up with the MPP. This is because the PV curve can have multiple MPPs and finding them all can be difficult. Under rapidly changing irradiance, the MPPT control system might not be able to react quickly enough, reducing the photovoltaic system's efficiency. Under rapidly varying irradiance conditions, as shown in Figure 12 PV curves can have multiple maximum points. Assuming point A as the starting point, the MPPT algorithm begins tracking the MPP. If primary perturbation direction is positive and reference voltage is raised to point B, the output power is observed to increase due to an increase in irradiance, causing the operating point to move to point C. Despite moving away from the MPP, the algorithm maintains to increase the voltage. During another change in irradiance, the operating point moves from C to E, and the algorithm observes an increase in output power during this perturbation period. Consequently, the algorithm raises the reference voltage in the same direction, resulting in point F, and the operating point moves even further away from the MPP. However, this process is not very clear as the algorithm depends on the output power value and cannot differentiate whether the increase is due to the operating point traveling towards the MPP or an increase in irradiance.

A. Partial shading condition solutions.

A drop in voltage occurs in a solar cell or group of cells whenever they are shaded by an obstruction such as a tree, a building, a cloud, or anything else (s). Failure can occur because the shaded cell(s) are now acting as a load instead of a generator. A bypass diode is used to prevent this from happening by rerouting the current away from the shaded cell(s) and into the load[22]. Figure 13 illustrates a single cell that experiences partial shading, while Figure 14 displays the P-V curve of a PV module with multiple maximum power points (MPPs) when partial shading occurs and the bypass diode is activated, resulting in global and local peaks. This is due to the shaded cells' inability to contribute to power generation, causing the operating point to shift away from the global MPP. When the operating point is at a maximum power point (MPP) of the unshaded cells, the output power is at its highest. Detecting the global peak under shading conditions can be challenging as local peaks are usually smaller than the global peak. This presents a difficulty in efficiently detecting the global peak. Most MPPT algorithms are not capable of distinguishing between local and global maximum power points, making it difficult to track the true MPP under partial shading conditions. While removing the bypass diode from the system could simplify the tracking process by reducing the number of peaks, it would also increase the cost of solar power

generation. Therefore, removing the bypass diode is not a viable solution.

CONCLUSION

To maximize the efficiency of photovoltaic (PV) system, several maximum power point tracking (MPPT) methods were used. This paper reviews the most commonly used MPPT techniques, both soft computing and conventional methods, selected from various literary works. The paper illustrates the principle of work and implementation for each technique. The paper also discussed the challenges that face the MPPT techniques, like partial shading and fast-changing irradiance conditions. However, the choice of MPPT technique will depend on the specific application and the environmental conditions that the PV system will be exposed to. Overall, the results of this study show that MPPT techniques are a valuable tool for improving the performance of PV systems. The use of MPPT techniques can lead to significant increases in efficiency and reliability, making them a cost-effective way to increase the value of PV systems.

CONTRUBITION OF THE AUTHORS

The contributions of the authors to the article are equal.

CONFLICT OF INTEREST

There is no conflict of interest between the authors.

STATEMENT OF RESEARCH AND PUBLICATION ETHICS

Research and publication ethics were observed in this study.

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