Classification and Comparison of Maximum Power Point Tracking Algorithms for Photovoltaic System: A Review

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Abstract - *Photovoltaic (PV) electrical power generation, as one of renewable energy source, is a technique which uses solar energy to produce electric energy. The utilization of such systems is growing because of limited resources and the acute energy crisis. This motivates the researcher community to reaches these renewable energy sources also to maximize their efficiency. This paper presents a literature survey from most up-to-date achievements in maximum power point tracking system AI algorithms. Maximum power tracking algorithms are used to match the load resistance to the supply input resistance to extend the power delivered from the photovoltaic system. This paper compares between the works done in these algorithms concentrating on the AI algorithms which have proven higher efficiency in this field. The paper additionally states the foremost recent contributions in every algorithm.*

Key Words: **Photo-voltaic (PV), Maximum power point tracking (MPPT), Traditional Control Techniques, Intelligent Control Techniques, Hybrid Intelligent Control Algorithms.**

1. INTRODUCTION

Recently, energy generated from clean, renewable, efficient, and environmental friendly sources has become one of the of the major research areas for scientists and engineers. solar power systems attract more research, among all renewable energy sources, because of their availability. Wide usage of photovoltaic systems led to the reduced cost of manufacturing, but still the problem of low efficiency of the solar panels. The output powers of PV system are crucially depending of the two variable factors, which are the cell temperatures and solar irradiances. This make the solar panel efficiency can reach 30-40%. This means that up to 40% of the incident energy is converted to electricity. The techniques to utilize effectively the PV are known as a maximum power point tracking (MPPT) method. These techniques are used to extract the maximum accessible power from PV module by creating them operates at the foremost efficient output.

In order to obtain the MPP we need a technique to force the controller to operate at the optimum operating point. Many tracking control techniques have been developed and implemented. The common techniques that has been used varies from traditional techniques such as Hill Climbing/Perturb and Observe, constant voltage to computational intelligence techniques such as neural network and fuzzy logic [1-2]. Actually, the intelligent control fields [3-5] have versatile control methods or algorithms like artificial neural networks, fuzzy logic, particle swarm optimization, artificial bee optimization, cuckoo search and evolutionary algorithms for a variety of tasks in control. These techniques are alternatives to get satisfying controllers by training employing a data set. At the same time, these techniques have some drawbacks such as failing to perform under partially shaded irradiance conditions, and their cost and complexity are high.

In this paper, a broad survey for the computational intelligence techniques and their application in tracking the MPPT in photo-voltaic system is presented. The entire paper is organized as follows. Section 2 briefly introduces the concept of MPPT. Section 3 is introduces the different traditional/conventional control techniques for MPPT. Section 4, presents the intelligent control techniques for MPPT. Section 5, introduces new hybrid AI techniques. Finally Section 6 presents the conclusions.

2. CONCEPT OF MAXIMUM POWER POINT

The maximum power point principle is based on the circuit principle: when the photovoltaic cell's output impedance and the load impedance are equal. The output power of photovoltaic cells is maximum. The control algorithm tracks the maximum power point which can be affected by climate conditions such as: temperature and irradiance. As shown in Fig. 1, the relationship between voltage and current is non-linear. Along the IV curve, there exists a point where the solar panel will output its maximum power; this is called the maximum power point. This principle seems easy to carry; however, there are several limitations due to local maximums and oscillations around the maximum point during the search for this point.

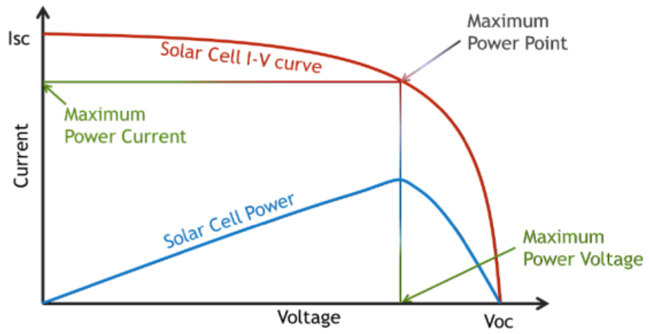

Fig -1: The relation between the characteristic I(v) of a cell and a load resistor.

Due to such limitations which can be summarized that the voltage power characteristic of a photovoltaic (PV) array is nonlinear and time varying because of the changes caused by the atmospheric and load conditions. The MPPT principles is to control the duty cycle for the pulse width modulation block that controls the power converter to deliver maximum power to the load as shown in Fig. 2.

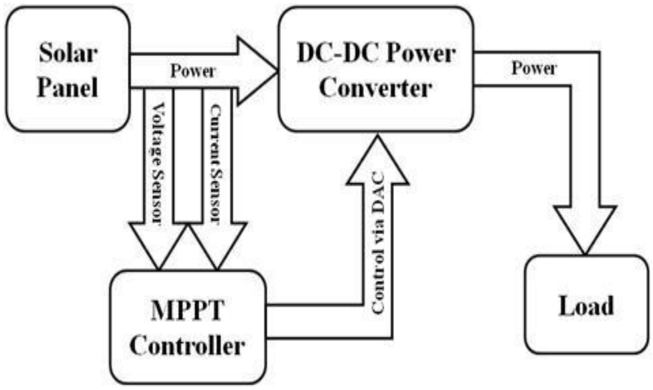

Fig -2: Block diagram of a MPPT controlled PV system.

3. MPPT TRADITIONAL CONTROL TECHNIQUES

3.1 Incremental conductance (INC) MPPT algorithm

INC is commonly used for solar PV MPPT. The incremental conductance method is based on the fact that the slope of the P vs. V (I) of the PV module is zero at the MPP, positive (negative) on the left of it and negative (positive) on the right of MPP. This technique deals with the sign of dP/dV without a perturbation which overcome the limitations of P&O technique [5].

dP/dV > 0 left side of the curve
dP/dV < 0 right side of the curve
dP/dV =0 peak of the curve

The above expressions can be expressed as (shown in fig. 4):

$$\frac{dP}{dV} = \frac{d\,(IV)}{dV} = I + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V} \qquad (1)$$

For MPP by putting $\frac{dP}{dV} = 0$, we get,

$$I + V\frac{\Delta I}{\Delta V} = 0$$

Hence,

ΔI/ΔV= -I/V , At MPP
ΔI/ΔV > - I/V, Left of MPP
ΔI/ΔV < - I/V, Right of MPP

Where,

I/V is instantaneous conductance,
ΔI/ΔV is incremental conductance,
VREF is reference voltage at which PV array is to be operated.

According to above equations the maximum power point of PV array can be tracked by comparing the I/V to ΔI/ΔV as shown in the flow chart (fig. 7).

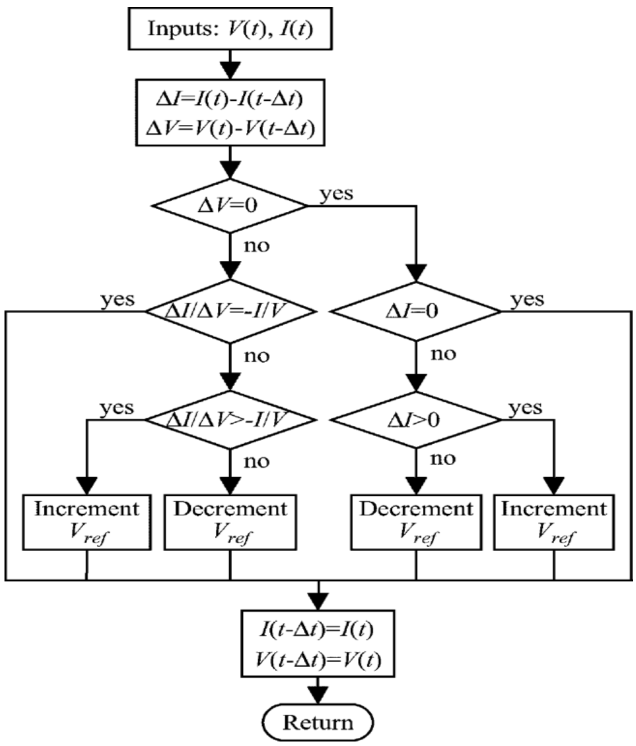

Fig -3: Flow chart of Incremental Conductance method.

When the MPP is achieved at that instant VREF must be equal to VMPP. And once it happens the operation is maintained at MPP until a change in ΔI is occur or the change in atmospheric conditions. The INC algorithm is continuously decreases or increases the VREF to maintain the new MPP. This method has advantages over P&O method like INC technique can track rapid change in atmospheric conditions. Also this technique determines when it has reached the MPP whereas the P&O technique oscillates around the same point [1], [2], [4]-[6], [8].

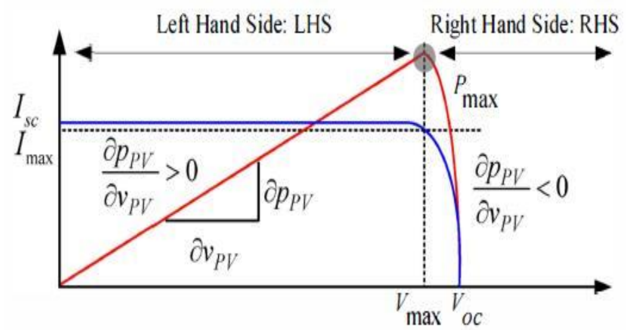

Fig -4: I-V and P-V curve and maximum power point of PV module.

3.2 Hill climb search (HCS) MPPT algorithm

The Hill climb search (HCS) MPPT algorithm is also called perturbation and observation (P&O) MPPT algorithm. In Perturb-and-observe algorithm method, we only use one sensor and hence it is very easy to implement. Voltage sensor used, senses the PV array voltage and so the cost of implementation is less among all other MPPT algorithm.
The Perturb-and-observe algorithm for maximum power point tracking is simplest techniques among all the MPPT techniques in literatures. It is based on the simple mathematical condition, i.e. dP/dV = 0, where P and V are power and voltage at output of PV module respectively.
From fig. 1, it can be seen that increase in voltage increases power when the PV array operates in the left of MPP and power decreases on increasing voltage when the same is operates in the right of MPP. Hence if dP/dV > 0, the perturbation should be same and if dP/dV < 0, the perturbation should be reversed. The process should be repeated periodically until dP/dV = 0 reached (maximum power point) [1], [3], [4], [7].

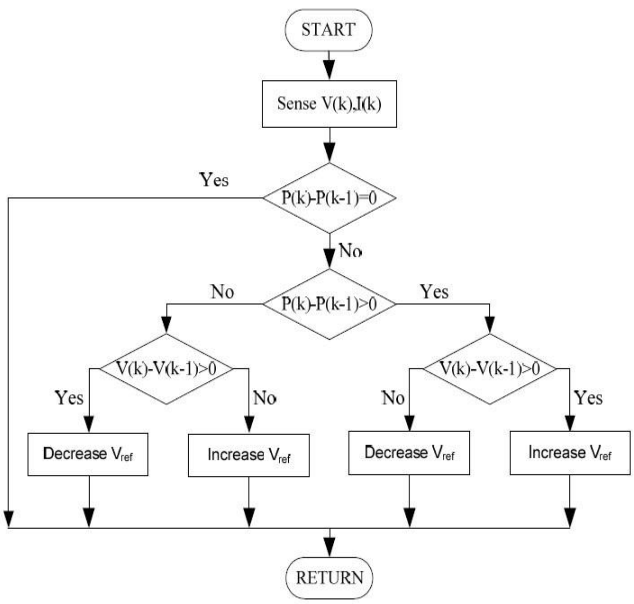

Fig -5: Flowchart of P&O method.

Under sudden changing atmospheric conditions P&O method does not respond well as illustrated in figure 6. Due to small perturbation of ΔV in the PV voltage V under constant atmospheric conditions the operating point moves from A to B. Since power decreases to B so according to P&O algorithm the perturbation should be reversed. And when the power curve shifts from P1 to P2 due to increase in irradiance the operating point will change from A to C. Now there is increase in power so again according to P&O algorithm the perturbation should be kept same which results in the divergence of operating point from Maximum Power Point [3], [4] and hence calculates the wrong MPP. To avoid this problem we can use incremental conductance method to track MPP correctly even under rapid change in irradiance.

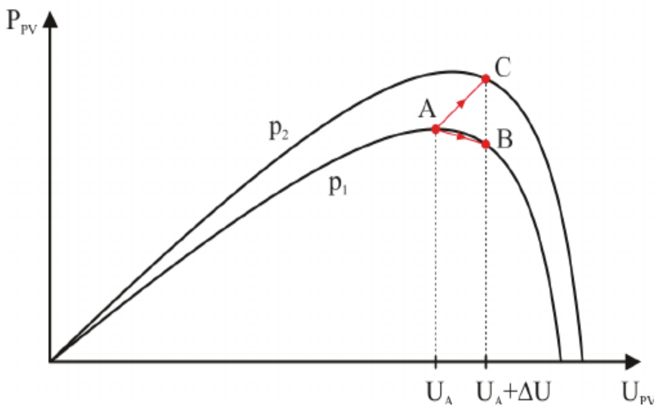

Fig -6: Divergence of P&O from MPP.

4. MPPT INTELLIGENT CONTROL TECHNIQUES

4.1 Fuzzy Logic

Fuzzy logic was 1st introduced by a great mathematician Loftih A. Zadeh of university of California at Berkeley. The theory wasn't popular at first and its applications weren't clear. Fuzzy logic control uses human expert knowledge to make control decisions. Fuzzy logic are often used in the treatment of unknown systems to model inexact data and experience |and skill} knowledge. The fuzzy controller block diagram is shown in Fig. 7. The fuzzification block is responsible for converting the numerical input variables to linguistic variables in accordance with the membership functions. The Fuzzy inference is that the process of formulating the mapping from a given input to associate output using fuzzy logic. The defuzzification block converts the linguistic output from the inference engine to numerical output values using the membership function. Fuzzy rule base refer to a set of predefined instructions which link the different values of crisp values with different subsets of fuzzy output space.

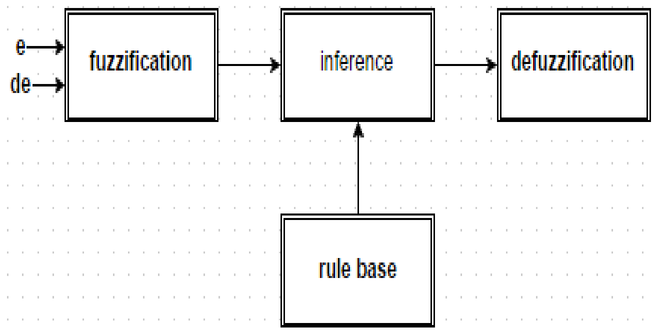

Fig -7: Fuzzy Controller Architecture.

The inputs to the fuzzy control are the error in the power and the change of error the output is the duty cycle variable that controls the pulse width generation block. The error is given by the following equation.

$$E(k) = P(k) - P(k-1) = V(k) - V(k-1) \quad (2)$$

The change in error is given by

$$CE(k) = E(k) - E(k-1) \quad (3)$$

The output of the fuzzy controller is that the duty cycle

$$(k) = D(k-1) + dD \quad (4)$$

A comparison between P&O and fuzzy controller for maximum power transfer under different weather conditions is introduced [9-10].A simulink model and a hardware implementation is presented [11-12]. A simulation and software implementation of fuzzy logic controller and a hardware implementation are presented [13].

4.2 Artificial Neural Network

Artificial neural networks are one of machine learning techniques which have been developed as generalizations of mathematical models of biological nervous systems. The learning capability of a synthetic neuron is achieved by adjusting the weights in accordance to the chosen learning algorithmic rule. The learning situations in neural networks may be classified into three distinct types, supervised learning, unsupervised learning and reinforcement learning. The most widely-used neural network for prediction is the single hidden layer feed-forward network.

There are two ways in literature for applied neural network controller in photovoltaic:

1- Using the neural network as a controller to regulate the duty cycle of the pulse width generator block. This allows the output resistance to match the load resistance.
2- The second method is using the neural network as a reference for the maximum voltage and current points Vm, Im, and using another controller such as fuzzy controller to track the maximum power point.

In this section, the previous work that uses the first method is presented, while the second method will be presented in the next section. In [14], a comparison between a neural network controller and P&O is presented and the simulation results show that ANN has fast and precise response under fast changes of solar irradiation. A PC based neural network controller for maximum power point tracking is presented [15]. A back probagation trained neural network MPPT controller is introduced [16]. A fast tracking algorithm under fast environment variations is presented [17]. In [17], differential evolution technique is used to train the neural network.

5. HYBRID INTELLIGENT CONTROL ALGORITHMS

5.1 ANFIS

The adaptive-neuro fuzzy inference system is a hybrid system that combines the potential benefits of both the artificial neural network and fuzzy logic. This technique has been employed in many modeling and forecasting problems.
A comparative study between neuro-fuzzy controller and P&O algorithm is presented [18]. The study proves the efficiency of the neuro-fuzzy controller. A simulation based comparative study between neuro-fuzzy and fuzzy controllers is introduced [19]. An ANFIS controller with cuk converter is presented [20]. An advanced neuro-fuzzy controller is introduced [21]. A comparative study between five different maximum power point tracking techniques including neuro-fuzzy is presented [22].

5.2 Intelligent P&O

Integrating the P&O algorithm with intelligent techniques will assist to enhance its performance and get better results. In [23] the authors present that the neural network enhanced P&O. In this work the neural network is used to decide the variable step for the P&O algorithm this enhances the algorithms stability and decreases the oscillations around the MPP. Decreasing the oscillations around the MPP reduces the power loss which is an important feature for this algorithm. The same idea can be implemented using fuzzy logic instead of a neural network [24]. In this paper a fuzzy logic block is introduced to control the step size of the P&O.

The second method is to replace the decision making blocks in the flow chart with the fuzzy logic controller. In this case the fuzzy controller produces the duty cycle for the pulse width generation [25-27].

5.3 Hybrid Genetic Algorithm

Genetic algorithm is the most important evolutionary algorithms. The genetic algorithm is an effective research algorithm that can search a large complex solution space for an optimum or near optimum solution. To optimize fuzzy controllers or to optimize neural network to control the MPP GA algorithms are used. The main idea of the genetic algorithms is to mimic the evolution theory. The algorithm reaches an optimal set of parameters using the "survival of the fittest" principle. A neural network genetic algorithm optimized controller is presented [22]. A fuzzy logic genetic algorithm optimized controller is introduced [23-24]. Other work introduces using the genetic algorithm as a controller for the maximum power point tracking and a comparative study is done [24-26].

5.4 Fuzzy-PID

The PID controller is a conventional controller which is used in most of the other control applications. The PID is stands for proportional integral differential controller. The output of the PID controller depends on three constant one for the proportional term and one for the integral term and the last one for the differential term. There are many methods for tuning the PID controller that is to find the proportional, integral and differential gains. The most widely used method in tuning the PID controller is the Ziegler-Nichols tuning formula. There are two approaches for using fuzzy logic and PID block in control the first approach is to use the fuzzy logic block as a tuning block for the PID controller. A new adaptive fuzzy PID controller for maximum power point tracking is introduced. The fuzzy block is used for tuning the PID controller online [27]. The work also introduces a comparison between the fuzzy tuned PID controller and the conventional PID controller and the P&O controller that proves the high tracking capabilities of the algorithm. The same idea was implemented in other work [28] the block diagram for this approach is given in Fig. 8.

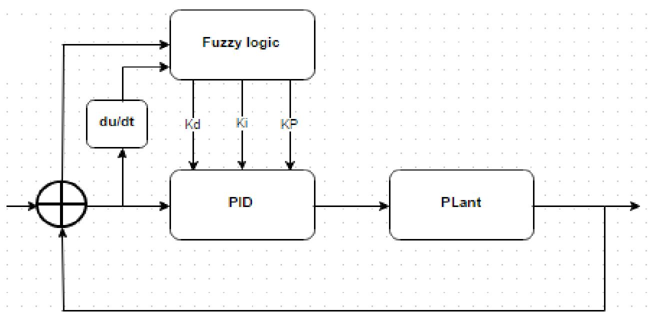

Fig -8: Fuzzy PID Controller Architecture.

The second approach is to use the fuzzy controller to introduce or to get some other control signal for the PID or the PI to work on an example of this approach is given [29-31]. The block diagram is shown in Fig. 9.

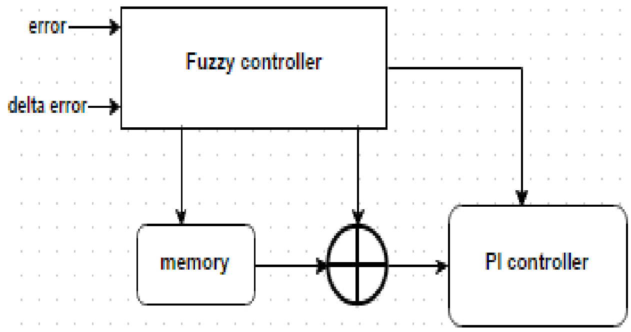

Fig -9: Fuzzy PI Controller Architecture

5.5 Ant Colony Optimization

The Ant colony optimization (ACO) is a probabilistic research algorithm for the optimum path. The Ant colony is used in the MPPT in two approaches: first as a direct controller to find optimum power point instead of finding the optimum path. The second approach as an optimizing tool for PI or Fuzzy controller. A novel Ant colony maximum power point tracking controller for PV systems under shading conditions was introduced [34]. A PI optimized controller for maximum power point tracking was also presented in [32]. A fuzzy controller optimized with Ant colony algorithm is presented [33].

5.6 Fuzzy-Neural Network

Instead of using the ANFIS controllers, there is another form of hybridization that combination of neural network and fuzzy algorithms. These type of hybrid techniques are always mentioned with two approaches in the literature. The first approach is to use the neural network to estimate some variable for the fuzzy logic controller [34-35]. The second approach is to use the fuzzy logic with Hopfield neural network to control the maximum power point [36-37].

5.7 Other AI techniques

In this section we will discuss other AI techniques which are not frequently referenced in the literature. A new neural network improved algorithm is introduced [38-39] the new algorithm uses a neural network to enhance the performance of the increment conductance algorithm. The neural network computes a reference voltage value for the algorithm to work on. The algorithm is tested on different irradiation and partial shading conditions. A fuzzy differential evolution controller is introduced.

6. COMPARISON OF MPPT TECHNIQUES

This section offers an outline of the most characteristics of the MPPT controller techniques presented in an exceedingly comparative means. However, the analysis of control techniques is completed along a set of analysis criteria. These include complexity, learnable, response time, and power consumption. The results are summarized in Table 1.

Table -1: Comparison of MPPT techniques with respect to several parameters

Techniques	Parameters			
	Complexity	***Learnable***	***Response Time***	***Power Consumption***
INCD	Simple	No	Slow	Loss
P&O	Simple	No	Slow	Loss
Fuzzy	Complex	No	Fast	Efficient
ANN	Complex	Yes	Fast	Efficient
ANFIS	Complex	Yes	Slow	Efficient
I P&O	Complex	No	Medium	Loss
Fuzzy PID	Complex	No	Fast	Efficient
GA	Complex	Yes	Fast	Efficient
AC-Fuzzy	Very complex	No	Fast	Efficient
Fuzzy-Neural	Very complex	Yes	Fast	Efficient

7. CONCLUSIONS

From many years researchers and scientists are working on renewable energy sources. MPPT is the technique for increasing the output efficiency and mainly used for solar system and play vital role in electrical energy generation. In this study, general classification and descriptions of the most widely used seven MPPT techniques are analyzed and compared to point out the advantages and drawbacks of various MPPT methods. This paper is helpful for selecting a MPPT technique depending upon various constraints as given in the table.

Intelligent controller techniques have higher performance in tracking the maximum power point. Moreover, they are efficient, adaptive and robust search methods producing near optimal solutions and have a large amount of implicit parallelism. However, the main drawback that plagues the intelligent techniques-based MPPT algorithms is its complexity, the large number of control parameters and high computations. Which are not suitable for low power applications.

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