Intelligent Techniques for MPPT Control in Photovoltaic Systems: A Comprehensive Review

Mohamed E. El Telbany, Ayman Youssef
Electronics Research Institution
Computer and Systems Department
{telbany, aymanmahgoub}@eri.sci.eg

Abdelhalim Abdelnaby Zekry
Ain Shams University
Communication and Engineering Department
abdelhalim_zekry@eng.asu.edu.eg

***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 research community to investigate these renewable energy sources and maximize their efficiency. This paper presents a literature survey from most recent achievements in maximum power tracking control AI algorithms. Maximum power tracking algorithms are used to match the load resistance to the source input resistance to increase 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 also states the most recent contributions in each algorithm. This manuscript should serve as a convenient reference for future work in maximum power tracking control.**

Keywords — MPPT, Photovoltaic Systems; Intelligent Control

I. 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. Among all renewable energy sources, solar power systems attract more research 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 available power from PV module by making them operates at the most 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 methods or algorithms such as 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 obtain satisfying controllers by training using 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 rest of the paper is organized as follows. Section 2 briefly introduces the concept of MPPT. Section 3 is introduces the different traditional control techniques for MPPT. Section 4, describes the intelligent control techniques for MPPT. Section 5, introduces new hybrid AI techniques. Section 6, describes an experimental results. Finally Section 7 presents the findings and conclusions.

II. 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 Figure 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.

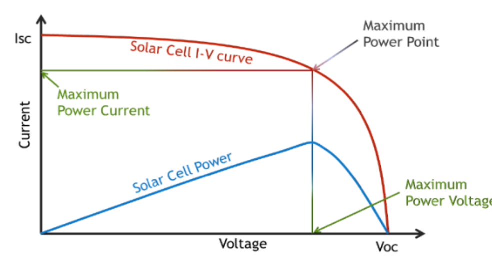

Figure 1. The relation between the characteristic I(v) of a cell and a load resistor.

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. Due to such limitations which can be summarized that the

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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 Figure 2.

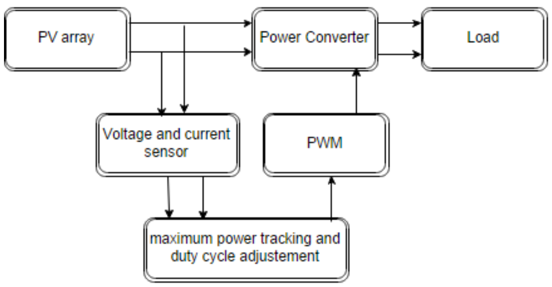

Figure 2. The MPPT Principles.

III. MPPT Traditional Control Techniques

1) *Incremental Conductance*

The incremental conductance maximum power tracking algorithm is the most commonly used method because it can perform precise control under rapidly changing atmospheric conditions without steady state oscillations. The incremental conductance method is based on the fact that the slope of the PV array power curve dp/dv is zero at the MPP, positive on the left of the MPP, negative on the right of the MPPT, and since

$$\frac{dp}{dv} = \frac{d(IV)}{dv} = I + V \cdot \frac{dI}{dv} \tag{1}$$

The previous equation can be transformed to the following equation.

$$\begin{cases} \frac{dI}{dV} = -\frac{i}{V}, & \text{at MPP} \\ \frac{dI}{dV} > -\frac{I}{V} & \text{left of MPP} \\ \frac{dI}{dV} < -\frac{I}{V} & \text{right of MPP} \end{cases} \tag{2}$$

The principle of this algorithm is shown in the Figure 3. A system for maximum power tracking using increment conductance and a cuk converter is implemented [7]. A simulation for a PV system under different weather conditions is presented [8]. A new incremental conductance algorithm with variable step size is introduced [9]. The influence of the incremental conductance parameters on the output power is evaluated and a comparison is done between the algorithm and other algorithms [10]. A comparison between incremental conductance and perturb and observe is introduced [11].

2) *Perturb and Observe*

It is the simplest method of MPPT to implement. In this method the power output of the system is checked by varying the supplied voltage. If on increasing the voltage, power is also increases then the voltage is further increased by dV. If on increasing voltage, power decreases then the voltage is further decreased by dV. The system oscillates around the MPPT when the atmospheric variations are minimum this can be solved by decreasing the step size this however have the disadvantage of slow controller that is the tradeoff between speed and oscillations in the perturb and observe algorithms The algorithm occasionally makes the system operation point far from MPP. The principle operation of this algorithm is shown in Figure 4.

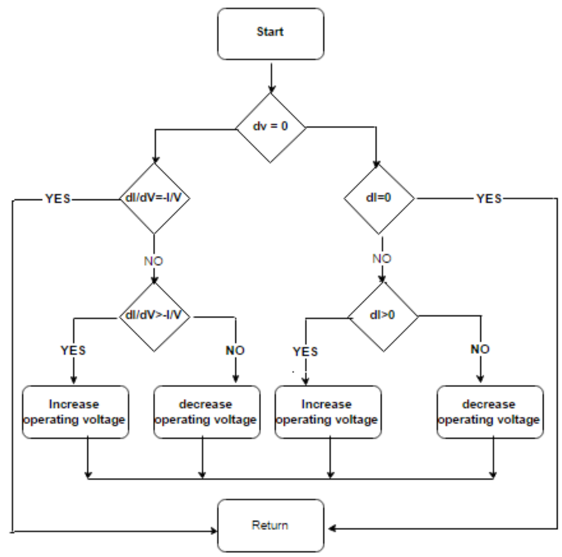

Figure 3. Increment Conductance.

It can be seen from the Figure 4, that it is needed to measure the current and voltage and the previous values of the current and voltage, then both the power value and the previous power value are calculated. Comparing the both values, it can be determine the next step whether to decrease or increase the voltage. A comparison between two distinct types of P&O algorithm is presented [12]. An improved method for P&O for PV systems is introduced in [13] the new improved has improved efficiency. Also an advanced P&O algorithm is introduced and compared with the simple P&O [14]. A Simulink model for the P&O algorithm and the simulation results are introduced [15]. In [16] a new variable step P&O algorithm is presented.

IV. MPPT Intelligent Control techniques

A. *Fuzzy Logic*

Fuzzy logic was first introduced by a great mathematician Loftih A. Zadeh of university of California at Berkeley. The theory was not very popular at first and its applications were not clear. Fuzzy logic control uses human expert knowledge to make control decisions. Fuzzy logic can be used in the treatment of unknown systems to model imprecise data and experience knowledge. The fuzzy controller block diagram is shown in Figure 5. The fuzzification block is responsible for converting the numerical input variables to linguistic variables in accordance with the membership functions. The Fuzzy inference is the process of formulating the mapping from a given input to an 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 pre-defined instructions which link the different values of crisp values with different subsets of fuzzy output space.

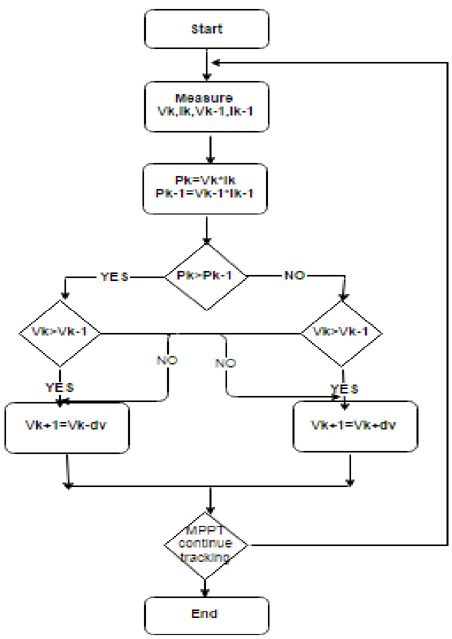

Figure 4. Perturb and Observe Technique.

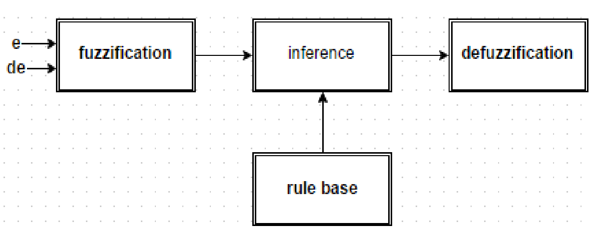

Figure 5. Fuzzy Controller Architecture.

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.

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{3}$$

The change in error is given by

$$CE(k) = E(k) - E(k-1) \tag{4}$$

The output of the fuzzy controller is the duty cycle

$$(k) = D(k-1) + dD \tag{5}$$

A comparison between P&O and fuzzy controller for maximum power transfer under different weather conditions is introduced [17-18].A simulink model and a hardware implementation is presented [19-20]. A simulation and software implementation of fuzzy logic controller and a hardware implementation are presented [21].

B. 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 an artificial neuron is achieved by adjusting the weights in accordance to the chosen learning algorithm. 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 methods in literature for applied neural network controller in photovoltaic:

1- Using the neural network as a controller to control 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 V_m, I_m 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 [22], 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 [23]. A backprobagation trained neural network MPPT controller is introduced [24]. A fast tracking algorithm under fast environment variations is presented [26]. In [26], differential evolution technique is used to train the neural network.

V. Hybrid Intelligent Control Algorithms

A. 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 [27]. The study proves the efficiency of the neuro-fuzzy controller. A simulation based comparative study between neuro-fuzzy and fuzzy controllers is introduced [28]. An ANFIS controller with cuk converter is presented [29]. An advanced neuro-fuzzy controller is introduced [30]. A comparative study between five different maximum power point tracking techniques including neuro-fuzzy is presented [31].

B. Intelligent P&O

Integrating the P&O algorithm with intelligent techniques can assist to enhance its performance and get better results. In [32] 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 [33]. 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 [34-36].

C. Hybrid Genetic Algorithm

Genetic algorithm is one of 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. GA algorithms are used to optimize fuzzy controllers or optimize neural network to control the MPP. 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 [31]. A fuzzy logic genetic algorithm optimized controller is introduced [32-34]. Other work introduces using the genetic algorithm as a controller for the maximum power point tracking and a comparative study is done [33-35].

D. Fuzzy-PID

The PID controller is a conventional controller that is used in many different control applications. The PID is an abbreviation for proportional integral differential controller. The PID controller output 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 [36]. 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 [37] the block diagram for this approach is given in Figure 8.

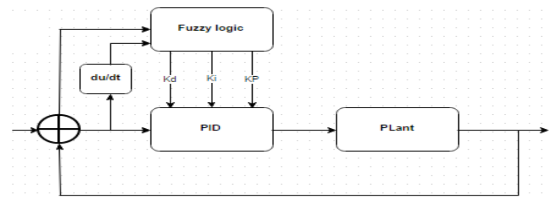

Figure 8. Fuzzy PID Controller Architecture.

The second approach is to use the fuzzy controller to introduce some control signal for the PID or the PI to work on an example of this approach is given [38-40]. The block diagram is shown in Figure 9.

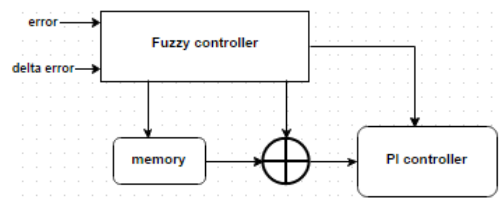

Figure 9. Fuzzy PI Controller Architecture.

E. 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 optimize tool for Fuzzy controller or PI controller. A novel Ant colony maximum power point tracking controller for PV systems under shading conditions was introduced [49]. A PI optimized controller for maximum power point tracking was also presented in [47]. A fuzzy controller optimized with Ant colony algorithm is presented [48].

F. Fuzzy-Neural Network

Instead of using the ANFIS controllers, there is another form of hybridization that combination of neural network and fuzzy algorithms. These hybrid techniques are always mentioned in the literature with two approaches. The first approach is to use the neural network to estimate some variable for the fuzzy logic controller [50-51]. The second approach is to use the fuzzy logic with Hopfield neural network to control the maximum power point [52-53].

G. Other AI techniques

In this section we discuss other AI techniques that are not frequently referenced in the literature. A new neural network improved algorithm is introduced [54-55] 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 [56].

VI. COMAPSION AMONG THE MMPT TECHNIQUES

This section offers an overview of the main characteristics of the MPPT controller techniques presented in a comparative way. However, the evaluation of control techniques is done along a set of evaluation criteria. These include *complexity*, *learnable*, *response time*, and *power consumption*. The results are summarized in Table I.

TABLE I. COMPARISON BETWEEN DIFFERENT MPPT TECHNIQUES.

	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 comp.	no	fast	efficient
Fuzzy-neural	Very comp.	yes	fast	efficient

VII. CONCLUSION

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 the large number of control parameters, its complexity and high computations. Which are not suitable for low power applications? This paper is mint to be a complete reference for intelligent algorithms for maximum power point tracking applications through surveying more than ten different techniques.

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