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Maximum Power Point Tracker (MPPT) for Photovoltaic Power Systems-A Systematic Literature Review

Mojtaba Kordestani, Member, IEEE, Alireza Mirzaee, Ali Akbar Safavi and Mehrdad Saif, Senior Member, IEEE

***Abstract*— Photovoltaic (PV) as a renewable source of energy plays a significant role in generating electricities in the industry and distributed consumers. The output power of the PV device is highly nonlinear which is dependent on I-P and V-P characteristics of the device and also irradiation conditions. Therefore, many research works have been performed to optimize the performance and obtain maximum power from the PV panels. This paper provides a brief literature review on maximum power point tracker (MPPT) for the PV panels. For this purpose, the PV circuit structure with its mathematics model is presented. Then, recent publications on various design methodologies are reviewed.**

I. Introduction

Technological advancements, environmental concerns, increasing demand for energy worldwide, and public policy have all contributed to increasing interest in renewable sources of energy. Amongst various sources of renewable energy, PV is a popular one. Given the fact that the PV panels do not contain any moving parts, they lead to a significantly lower maintenance cost of compared to other systems. Moreover, the PV system can be easily used for stand-alone purposes [1]. However, nonlinear nature of the PV system originating from its dependency on weather conditions, such as irradiation and temperature, makes it difficult to operate on maximum power points in terms of $I-P$ and $V-P$ characteristics. As a result, many maximum power point tracker (MPPT) algorithms have been introduced by researchers to operate the system at optimum operating point [2], [3].

Generally, MPPT technique can be divided into two separate categories: direct and indirect approaches [1]. The direct approach of the MPPT algorithm is not required to have a prior knowledge about the PV characteristics. Perturb and Observe method [4], [5], incremental conductance method [6], [7], fuzzy logic (FL) method [8], [9] and neural network (NN) method [10] are considered as direct methods. The indirect approach uses the mathematical relationships of the system to maximize the power. The indirect approach includes open-circuit PV voltage method [11], short circuits PV current method [12].

M. Kordestani is with the School of Electrical and Computer Engineering, University of Windsor, 401 Sunset Avenue Windsor, O. N., N9B 3P4, Canada. kordest@ uwindsor.ca
A. Mirzaee is with the School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran. alirezadmirzaei@gmail.com
A. A. Safavi is with the School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran. safavi@shirazu.ac.ir
M. Saif is with the School of Electrical and Computer Engineering, University of Windsor, 401 Sunset Avenue, Windsor, O. N., N9B 3P4, Canada. msaif@ uwindsor.ca

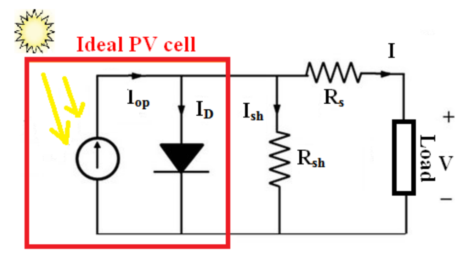

Fig. 1: An equivalent circuit of the PV.

In addition to the above, another distinction is made by considering the exchange of information, i.e., offline versus online approaches. The offline or open loop MPPT approach applies the historical testing data of the system like open circuit voltage or short circuit current of the PV panel. There are numerous methods in this group such as neural network [13], [14], genetic algorithm [15–17]. The online approach considers real-time data from the system. Thus, it provides a better accuracy in results. The online approach consists of variety of algorithms such as perturbation and observation (*P&O*) [18–20], incremental conductance [21], [22], and ripple correlation control (RCC) [23].

In this literature review, we focus on the PV panel and various methods for the MPPT. The main goal is to provide recent technology achievements on the PV panels.

The paper is organized as follows: Section II illustrates a model of the PV panel and provides its mathematical formulation. In Section III, a review of direct and indirect methods are provided. Then, various online and off-line methods are illustrated in Section IV. Finally, related design problems, conclusions, and future guidelines are discussed in Section V.

II. System description

PV arrays consist of a large number of series and parallel solar cells [24]. Such a system can be modeled by a current source, a shunt diode, and series resistor. Figure 1 shows an equivalent circuit of the PV system.

The single diode model can be a simple equivalent circuit to illustrate the PV cell. A current source is in parallel with a diode and it is directly proportional to the irradiation. The current of the PV cell, which is known as a Shockley diode

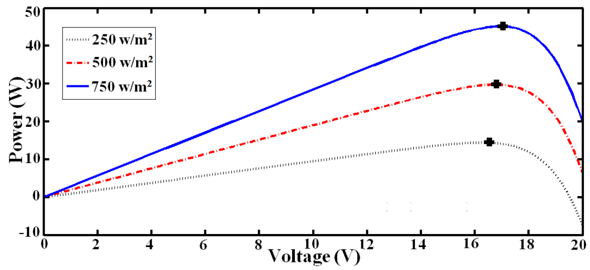

Fig. 2: Relationship between output voltage and power of the PV cell under different irradiation conditions

equation, is computed as follows:

$$I = I_{ph} - I_D = I_{ph} - I_0(e^{\frac{q(V_a+IR)}{nKT_a}} - 1) \quad (1)$$

where variable I is current of the PV cell, variable I_{ph} denotes photocurrent, parameter q indicates elementary charge with a value of $1.60217646e^{-19}$ C, n implies the diode ideality factor, parameter k signifies Boltzmann constant, variable T_a represents ambient temperature and variable V_a shows terminal voltage of the PV cell. Furthermore, parameter I_0 points out dark saturation current or diode saturation current which is always generated when there is no light irradiation to the PV cell [25]. Figure 2 illustrates the relationship between output voltage and power of the PV cell under different irradiation conditions.

It is clear from Figure 2 that under a certain irradiation, there is a unique maximum point located at the knee of the curve. Furthermore, this value changes with respect to variation in the irradiation.

III. Direct and Indirect Methods for MPPT in the PV Panels

In this section, various direct and indirect methods are demonstrated.

A. Direct methods

Direct methods use the measurement data and computation techniques to maximize the power in the system. The most famous methods in this category are reviewed as follows:

1) Perturb and Observe (P&O) methods: The main mechanism for the perturb and observe method is simple. This method measures voltage and current of the PV panel and calculates the power. Then, it compares the result with the previous power. After this, the controller changes the duty cycle of the pulse width modulation to enhance the power in the system. The design procedure is straightforward. If the computed power is greater than the previous one, the controller holds the same direction for the duty cycle. However, if the power declines, the controller changes the direction of the duty cycle. In some research works, the perturb and observe method is also known as hill climbing (HC) algorithm [26].

It must be noted that the performance of the perturb and observe controller is high in the environment without disturbance. However, the controller provides a slow tracking which does not have a proper performance in rapidly changing conditions [27]. Therefore, the perturb and observe method often combines with other methods to improve the performance of the method in the presence of the disturbance and varying environments.

A new start-stop mechanism based on the perturb and observe method is introduced in [28] to remove the steady-state oscillations in the power response and maximize the power. The main aim is to improve the power performance by reducing the perturbation magnitude. However, this method reduces the speed of the system in fast irradiation conditions. Therefore, a tradeoff is made between the speed and steady-state oscillation in the system. The proposed method is evaluated in a subMICs-based PV system and the experimental test scenarios show the performance of the system. An integrated method using the perturb and observe method and fuzzy logic technique is developed in [29] to operate at maximum power output in the presence of variation in solar radiation. The proposed method shows a high performance under varying irradiation conditions. A modified perturb and observe algorithm is presented in [30] to solve the problem of local maximum for the MPPT. The suggested method adds a checking algorithm to the conventional perturb and observe method to monitor all existing maximum powers and then decide how to change the controller to achieve a higher power in the system. The proposed method is validated in two environments consisting of constant and varying irradiation conditions.

2) Incremental conductance (IC) method: The Incremental conductance method is developed to address the drawback of the perturb and observe method. The method reduces the tracking time and enhances the power in varying environments [31]. The IC method considers the relationship between current and voltage ($\frac{-I}{V}$ or $\frac{-\delta I}{\delta V}$) to adjust the controller and achieve the maximum power [31]. However, a fixed step mechanism is considered to modify the controller which may take relatively long time to reach the maximum power. Therefore, the performance is still slow in varying conditions.

A new IC method is proposed in [32] for nonlinear load. The proposed IC method considers a combination of the conductance and the rate of the conductance to deal with nonlinearity of the load. The suggested method can easily deal with the voltage ripple and provide the MPPT. Simulation results show that the suggested method enhances the maximum power in the PV panel. In [33], An IC method using a PI controller is developed for optimizing power in the PV panel. The method uses a converter with a V-shaped impedance component to generate a higher voltage in comparison with other conventional converters. For test study, three cases including various temperatures, light intensity changes, and load uncertainty are considered. The test results indicate a proper response of the PV panel in all cases.

3) Fuzzy logic (FL) methods: Fuzzy logic is an intelligent method which can describe a system with linguistic rules using membership functions [34]. The fuzzy logic can be

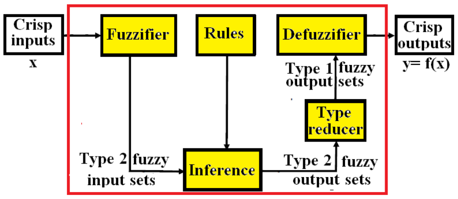

Fig. 3: Type 2 fuzzy inference system structure.

considered in the PV panels to model uncertainty and nonlinearity in the system and formulate the MPPT problem.

A combination of fuzzy logic technique and the perturb and observe method is designed to improve the maximum power in PV panel in [35]. The proposed method utilizes power variation and voltage variation as input to the fuzzy system instead of using error and its variation which enhance the performance of the method. Then, an implementation is performed using the dsPIC digital signal controller (model: $dsPIC33FJ16GS502$). The experimental test results validate the effectiveness of the method. Furthermore, the fuzzy logic-based controller provides a faster tracking in comparison with conventional fixed step perturb and observe method. A fuzzy logic controller via incremental conductance method is introduced in [36] to optimize the power point tracking in PV panel. The main purpose is to build some fuzzy rules based on conductance formula to achieve the maximum power for the PV panel in varying irradiation and temperature conditions. The simulation results show the capability of the proposed system in various weather conditions. A type 2 fuzzy controller is considered in [37] to achieve the MPPT in a solar cell. Simulation result shows a fast response under changes in the atmospheric conditions. Fuzzy logic type 2 controller (FLC) is designed based on fuzzy logic theory. Figure 5 illustrates type 2 fuzzy inference system structure. The type 2 fuzzy system includes fuzzifier, rule base, defuzzifier, inference engine and type reducer. This structure is similar to type 1 fuzzy inference system. The only difference is the type reducer which is added to the type 2 fuzzy system. It means the method can be formulated in the same way that a type 1 fuzzy system is developed. Due to this fact, this method is also known as interval type 2 fuzzy logic controller (IT2FLC) [38]. The appropriate modeling of uncertainty helps the type 2 fuzzy system achieve a higher accuracy.

4) Artificial Neural network (ANN) methods: Artificial neural networks are intelligent methods which can model a system with available input-output data without knowing about the physic of the system. Therefore, the neural networks are known as a block box system [39]. The ANNs are considered to model highly nonlinear systems and reach more accuracy in estimations.

An Intelligent technique using feed-forward and Elman neural networks is presented in [40] to forecast the power of the PV panel. Two-year data from the PV panel is used to train and test the proposed method. The structure of the networks must be selected with respect to the nature of the data. The simulation results show that both of the networks have a proper performance. An adaptive Neuro-Fuzzy inference system (ANFIS) is presented in [41] for the high performance tracking in PV panel. The proposed method combines the learning capability of the ANN and FL to improve the accuracy of the system. Therefore, the suggested method is suitable to handle a nonlinear load or varying conditions. Several simulation tests show a higher accuracy of the ANFIS method in comparison with the fuzzy logic.

B. Indirect methods

The indirect method requires a prior knowledge about the PV system to optimize the power. In the following, a review of methods in this group is demonstrated:

1) short circuits PV current methods: This method makes a linear relationship between cell short circuit current and the maximum power. The maximum power is about 90% of the short-circuit current [42]. A new method for modelling PV panel is presented in [43] by considering short-circuit current (I_{sc}). The proposed method provides more accurate prediction of the PV panel at small times scale. The test results show that differences in module tolerances may lead to an error in estimation of the model.

2) open-circuit PV voltage methods: An indirect method using open circuit voltage is proposed in [44] for the PV panel. The simulation results show that the suggested system is robust in a wide range of operating conditions. A new combined algorithm based on fractional open circuit voltage, short circuit current, and incremental conductance is introduced in [45] for maximising the power of the PV system. For this purpose, the proposed method estimates the open circuit voltage or short circuit current. Then, the maximum power is determined using incremental conductance algorithm. Experimental test results using kit DSpace DS 1104 indicate a high performance of the system in varying environmental conditions.

IV. On-line and off-line methods for MPPT in the PV panels

This section illustrates the classification via on-line and off-line methods for the MPPT in the PV panels.

A. Online MPPT methods

Online methods update their information over time and consider new measurement data to optimize the system. In the following, different online methods are considered.

1) Perturb and observe (P&O) method: The Perturb and observe is an adaptive method in nature. However, as we mentioned before, the performance of the method is weak in varying environmental conditions. In this section, the modified Perturb and observe methods are considered to deal with rapidly changing environments. A new adaptive MPPT technique is developed in [46] for the PV panel. The proposed method utilizes a combination of a binary-weighted step and monotonically decreased step to stabilize the power fluctuation in the system. The proposed controller

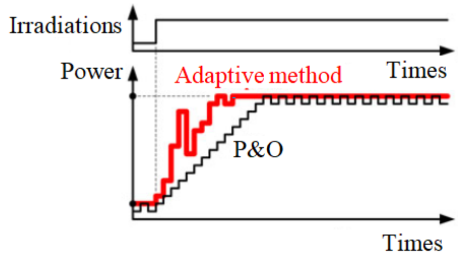

Fig. 4: Adaptive MPPT method and perturb and observe method under a step change in irradiation condition [46].

adapts with the new environment and remains unchanged until a new irradiation condition. The experimental results in varying environments show a better response of the proposed method in comparison with the conventional perturb and observe method. Figure 4 illustrates the response of the proposed adaptive MPPT technique and perturb and observe method under a step change in irradiation condition.

It is noted from Figure 4 that the new adaptive method can track faster compared to conventional perturb and observe method.

2) Incremental conductance: Similarly, the incremental conductance is an adaptive method. However, it originally uses a fixed step to reach the maximum point which makes it be slow. Therefore, new modified IC method applies variable steps. Moreover, the new technique often integrates the conventional IC method with other methods to improve its performance and make it faster. An adaptive incremental conductance method is introduced in [47] to reach to the maximum power in various operating conditions. The proposed method applies the fractional-order incremental conductance to capture a dynamic mathematical model of the system. Simulation results show the performance of the PV panel in varying conditions. An adaptive robust MPPT is developed in [48] for the PV system. The proposed method utilizes a sliding surface to design a robust controller for the system. Then, the incremental conductance method is utilized to obtain the maximum power of the PV panel. The robust stability is shown by the Lyapunov theorem. Simulation results indicate an improvement in the tracking power compared to the conventional IC method in varying conditions.

3) Ripple correlation control (RCC): The MPPT method based on the ripple correlation control (RCC) applies a 100 Hz ripple on the ac line to track maximum power of the PV panel. Since the 100 Hz ripple is insensitive, it does not perturb the system. [49].

A combination of the RCC and FL methods is developed for a single-stage PV system [50]. The proposed method applies the product of voltage and power ripple to track the MPPT in the system. Simulation results show that the integrated system works under various irradiation conditions. A modified MPPT method based on the RCC technique is presented in [51] for single-phase voltage source inverter connected PV system. The suggested algorithm utilizes a mean function instead of first-order high pass filters and low-pass filters to track the MPPT of the PV panel. This method produces a sinusoidal current with a unity power factor. It is noted that the proposed method provides a higher accuracy for the MPPT in varying conditions.

4) Advance adaptive control methods: Advance control systems apply modern control method like feedback linearization, sliding mode control, pole placement and etc. Therefore, these methods provide a higher performance for the PV panel. However, the mathematical model of the PV system is often required in these methods.

An adaptive sliding mode controller is introduced in [52] to cope with an uncertain mathematical model of the PV panel. The proposed method neither need to measure the voltage output nor require the upper bound of the voltage. The proposed robust method estimates the voltage. The simulation results indicate the robust tracking performance of the system. In [53], a state feedback linearization method is developed to control a multilevel PV inverter. For this purpose, a nonlinear state model of a three-level inverter is considered. Then, the nonlinear model is converted into two linear subsystems. A feedback control method using pole placement is applied to track the maximum power using a variable step size via incremental conductance technique. The proposed method achieves a higher speed and tracking accuracy in comparison with the fixed step size incremental conductance approach. An advanced control methodology is introduced in [54] to track the maximum power in PV system. The proposed method is based on an integration of second-order sliding mode method and fuzzy logic technique. The second-order sliding controller could deal with the non-linearity of the PV panel and it is more robust to uncertainty in the system and therefore It has a better performance in varying conditions. The gain of the controller is tuned by the fuzzy logic membership functions. The performance of the proposed method is evaluated through simulation and experiment which shows an improvement of 1.5% in comparison with the conventional sliding mode control.

B. Off-line MPPT methods

Off-line or open loop methods consider the testing data of the PV system. In here, various off-line methods are discussed as follows:

1) Artificial neural network (ANN) methods: ANNs can model nonlinear systems. Therefore, they are considered in the PV panel for function approximation purpose. To apply ANNs, historical data of the PV panel is needed. This data is usually used to train the network with an off-line mechanism.

An intelligent off-line method using two cascaded ANN is presented in [55] to optimize the MPPT for the PV panel. The first ANN is responsible to predict the temperature and irradiation level from the voltage and current of the panel. The second ANN is utilized to estimate the maximum power from the predicted temperature and irradiation of the first network. The test results show the capability of the

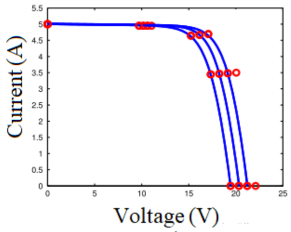

Fig. 5: The optimal five points for modelling PV panel [57].

proposed cascade ANNs especially in unstable environmental conditions.

2) genetic algorithm: An optimization method based on the genetic algorithm (GA) is presented in [56] for the PV panel. The suggested method searches for the global maximum power point in the system. Furthermore, the suggested GA algorithm uses the perturb and observe method to narrow down the search window and achieves a higher accuracy and less amount of computation. Simulation results indicate that a high performance of the proposed algorithm. Moreover, the desired performance is obtained with fewer numbers of iterations in a short time. A new intelligent method based on the GA is introduced in [57] to identify the mathematical model of the PV system in outdoor conditions. The nonlinear model of the PV panel is obtained using five operating points via GA. Figure 5 illustrates the optimal five points for modeling PV panel. The identified model is used for the MPPT in various irradiations and temperature conditions. The main advantage of the proposed method is less computation complexity as it only requires five operating points.

V. Related Design Problems, Conclusions and Future Guidelines

This paper reviewed the most recent control methods for maximizing power in PV panels. The basic concepts of the methods with their advantages and drawbacks were illustrated. In the following, some conclusions and future guidelines are provided:

1-The perturb and observe method and incremental conductance method can be easily implemented and have an acceptable performance in stable environments. However, their performances are low in varying conditions. These methods can be combined with other methods like fuzzy logic, genetic algorithm and etc to be suitable for rapidly changing environments.

2- Recently, advance control technologies such as siding mode, feedback control have been noticed for the PV system due to their accurate results. Therefore, adaptive advance control methods are highly appreciated to deal with varying conditions such as changes in temperature or irradiation.

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