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Maximum Power Point Tracking Controller for PV Application

Trends and Challenges

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***Abstract*—The maximum power point tracking (MPPT) controller is an important part of photovoltaic (PV) systems because of its capability to consistently maintain extracting maximum power at any given time and in various conditions. This paper reviews the MPPT methods for PV systems application. Several MPPT algorithms have been presented in literature, from simple to complex methods. All methods must be embedded in a power conditioner, usually a DC-DC converter, which serves as the controller media for the MPPT controller in PV systems application. Trends, existing problems, and the challenges of the MPPT are presented in this paper. Intelligent technology is trend in the development of intelligent MPPT. The major challenge is the ability of MPPT in dealing with various changes of the PV system and environmental conditions.**

Keywords—photovoltaic, maximum power point tracking, renewable energy, intelligent technology, trend, challenge

I. INTRODUCTION

Renewable energy (RE) sources are considered as the best options for sustainable energy supply because of the diminishing supply of conventional energy sources, such as fossil fuels, and their increasingly widespread negative effects on the environment. The photovoltaic (PV) generation system is one of the promising RE technologies, and it is considered as a clean and environment-friendly source of energy [1]. PV systems generate electricity from sunlight, without causing pollution and depletion of materials. Research and applications in this field are geared toward improving the efficiency and effectiveness of PV systems, especially in the energy conversion process of solar light and the powering up of electronic devices.

One of the main problems in PV system power generation is the low conversion efficiency of about 9% to 17%, which is mainly due to the low irradiation of the sine, and the electrical power generated by a typical PV panel varies with weather conditions [2-3]. Therefore, several researchers enhanced electrical energy generation using the PV system. When a PV system is operated at its maximum efficiency, the size of the PV array, power conditioner, and other parts of the system become smaller, thereby reducing system investment. Other factors that affect the efficiency of PV conversion is the solar cell voltage–current (V–I) and voltage–power (V–P) characteristics, which are not linear; the influence of irradiation varies with temperature. Each line of the various V–I and V–P curves has a unique point, which is referred to as the maximum power point (MPP). A PV cell/panel produces maximum power when the voltage or current is at the MPP of each characteristic curve. Hence, a PV generation system should operate at its maximum output power to increase its efficiency and to reduce the capital cost of the system, and thereby maximize the return on investment (ROI) of the PV system. The position of the MPP at any time is not known, but it can be tracked using a search method. However, the MPP also changes with the irradiation level and temperature due to the nonlinear characteristic of PV modules [4]. Each type of PV module has its own specific characteristic, which complicates the tracking of MPPs. Several maximum power point tracking (MPPT) algorithms have been developed to overcome this problem [5-7].

The MPPT algorithm is usually embedded in a controller that consists of a digital signal processor and a DC–DC converter [6-8]. The device controlled by an MPPT algorithm is called an MPPT controller. An MPPT controller extracts the amount of power available from the PV array. This function will help increase the ROI of PV system development.

This paper investigates the MPPT controller for PV application on various aspects. Trends, existing problems, and the challenges of this technology are explained in detail for future development.

II. MPPT CONTROLLER IN THE PV SYSTEMS

In general, PV systems are classified according to their functional and operational requirements, component configuration, and connection to the electrical loads and other power sources. The two principal classifications are grid-connected and stand-alone system configurations [9-10]. The first stand-alone PV system application is used in telecommunication and satellite programs [11]. Currently, the major applications of these systems are in remote area power supplies [1, 12] and building-integrated photovoltaic systems [13-14].

Power conditioner devices in PV systems are used for protection and control, such as DC–DC converters, charge regulators, and inverters [15-16]. These devices process the electricity produced by a PV system to enable such devices to meet the requirements of the load [17]. The devices allow the PV generator to work as close as possible to its maximum power point, which optimizes energy transfer and then results in a more efficient system [18]. Power conditioners are used depending on the type of PV system applications. A typical power conditioner made up of several DC–DC converters and DC–AC inverters for a grid-connected PV system was presented [19]. The DC-DC converter acts as the MPPT controller to optimize energy extraction from the PV panel. A DC–DC converter of the power conditioner for PV system operation at the MPP was described by [20]. Furthermore, the DC–DC converter is used to step-up the DC voltage from PV panel to meet the requirement input of the inverter.

A. *Standalone PV Systems*

A PV system designed to supply specified DC or AC electrical loads, which will operate independently from the electric utility grid, is called a stand-alone PV system. This type of PV systems may be developed only by a PV panel, or can be combined with wind turbines, a generator set, or other backup power source, hereinafter referred to as a PV-hybrid system [21].

Direct-coupled PV systems have no power converter interface and electrical energy storage (batteries). The systems can only operate with the presence of sunlight. Direct-coupled PV systems are suitable for common applications, such as farm water pumps, small circulation pumps for solar/thermal water heating systems, and ventilation fans. The critical part in designing the direct-coupled system is in matching the impedance of the electrical load to the MPP of the PV operation [10, 22].

Another application of stand-alone PV systems is the use of an electronic DC–DC converter for an MPPT of the PV array. The converter is an interface between the PV array and load, which improves the use of the available PV array maximum power output [10, 22]. Fig. 1 shows the schematic diagram of a stand-alone PV system with a DC–DC converter.

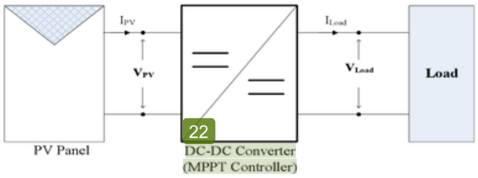


Figure 1. A stand-alone PV system with a DC–DC converter

Improving stand-alone PV system involves the use of batteries for energy storage [9]. Fig. 2 shows a diagram of a typical stand-alone PV system with energy storage (batteries) for powering load. Fig. 3 shows a diagram of a hybrid PV system with energy storage that powers DC and AC loads and also adds one or more backup power sources, such as wind turbines and motor-generator sets.

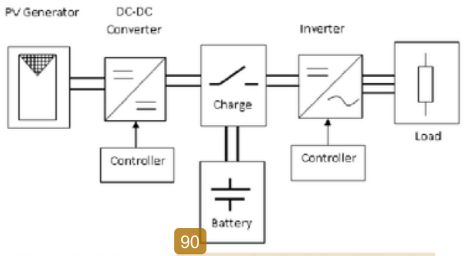


Figure 2. Schematic diagram of a stand-alone PV system

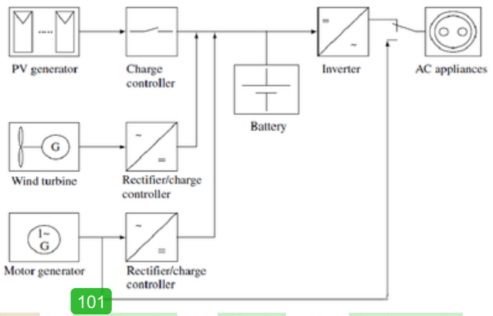


Figure 3. Hybrid system with PV, wind turbine, diesel generator, and battery storage [23]

B. *Grid Connected PV Systems*

PV systems that are designed to operate in parallel and are interconnected with the electric utility grid (Fig. 4) refer to grid-connected PV systems [24-26]. The important equipment in the system is the inverter, as well as the DC–DC converter and the MPPT controller [27]. The inverter is used to convert the DC power from the PV array into AC power, which is synchronized to the voltage and frequency of the utility grid. The inverter should automatically disconnect from the utility grid when the grid is down. A bi-directional power converter is used between the PV system and the utility grid in a typical distributed generation (DG) application [23, 28]. The on-site electrical loads in grid-connected PV systems are supplied by the power produced by the PV system and the utility grid system; the power output of a PV system is less than the on-site load demand. When the electric load demand is less than the power output of the PV system, the excess power from the PV system is contributed to the utility grid system. The safety features and power balance must be met in all grid-connected PV systems to ensure that the PV system will automatically stop its operation and feedback to the utility grid when the grid is shut down for repair [9, 27, 29-30].

Typically, the power conditioner for a grid-connected PV system includes a boost or buck-boost converter to adjust the voltage level available from the PV array voltage to the inverter. This system is called multiple power stages system [31]. An MPPT controller is usually embedded in the front end converter of the power conditioner to maximize the power harvest from the PV array [32].

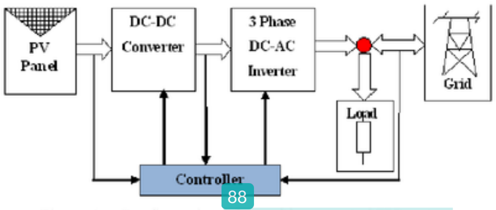


Figure 4. Configuration of a grid-connected PV system

C. *MPPT Controller Based PV System*

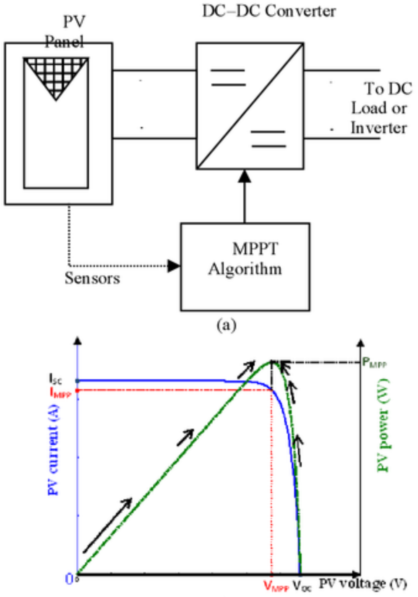
Optimizing the operation increases the ROI of the PV, such as extracting maximum power from the PV array continuously at every ambient condition [33-34]. The output power of PV systems are maximized by operating them close to the MPP [10, 35]. However, the position of the MPP on the PV module strictly depends on solar irradiation and temperature [10]. To achieve this goal, an MPPT controller is required to track the MPP continuously. An MPPT controller is an electronic system that plays an essential role in the PV modules operation to produce maximum power according to the situation [36]. The MPPT controller is usually implemented with a boost converter and is connected between the PV panel and load [15-16, 24]. Fig. 5 shows the role of an MPPT controller in a PV system. The DC–DC converter is controlled by an MPPT algorithm to draw current or voltage at the MPP, thus, the maximum power available from the PV is delivered to the load. The arrows on the V–P curve indicate that the MPP can be tracked from both sides and then oscillated around the MPP.

III. CURRENT MPPT TECHNIQUES

The MPPT algorithms that are applied in the PV system can be classified into two types: offline- and online-based methods or real time-based methods [10, 37]. Early MPPT algorithms involved simple techniques, such as the voltage and current feedback-based MPPT, and were later developed into more complex and improved MPPTs that considered perturbation and observation (P&O) and incremental conductance (IC) methods [2, 5, 37]. The classification of MPPT methods is summarized in a tree diagram in Fig. 6.

A. *Offline Methods*

Offline MPPT methods use the correlation of a database of measured parameters, such as short circuit current, open circuit voltage obtained from the typical V–P curves generator for different irradiances and temperatures, or the use of mathematical approximations from empirical data to approximate the MPP [10, 37]. Examples of offline MPPT methods are the curve-fitting method, the look-up table method, the CV, which is also called the fractional of open circuit voltage (FOCV) of PV generator method, and the constant current [38] or fractional of short circuit current of PV generator method [37, 39]. The advantage of offline MPPT methods is their simplicity. However, these methods only provide an approximation of the actual MPP, not the actual MPP.



(a)

(b)

Figure 5. Concept of an MPPT controller for PV system: (a) configuration, and (b) tracking

1) *Curve-Fitting Method*

The curve-fitting method uses a database of parameters that include data from typical V–P curves of PV systems for different irradiances and temperatures [40-41]. The developed mathematical model is based on empirical data. The model contains V–P characteristics of the PV panel in electrical power generation [42]. The voltage at the MPP is estimated based on the model.

The drawback of this method is that the model applies only to a specific solar cell. The model should also be updated properly because of the changes in solar cell characteristics as the material ages. Furthermore, the establishment of a mathematical model requires a large memory capacity.

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2) *Constant voltage algorithm*

CV, also called FOCV PV panel algorithm, is based on the observation from the PV characteristic I–V curves, which is the ratio of the array's maximum power voltage (VMPP) to its open-circuit voltage (VOC) known as constant ratio (K) [43]. The effect of ambient variations is not considered in this method. The advantage of this method is its simplicity. However, the method should carefully define the optimal value of the constant, which ranges form 0.73 to 0.8 [37, 43]. Therefore, the tracking efficiency of this method is low because it always interrupts the PV operation during periodic measurements of the open circuit voltage of the PV panel.

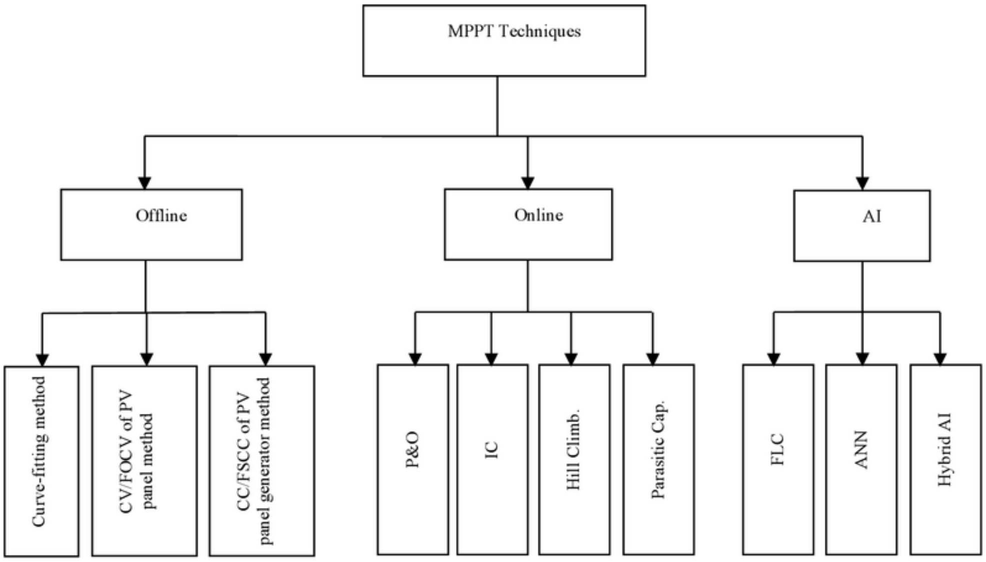

Figure 6. Classification of MPPT techniques

3) *Constant current algorithm*

A similar method uses a fraction of the current at maximum power (IMPP) to the short circuit current (ISC) from the PV panel I–V curves. This method uses a switch to generate a short circuit in the PV panel terminal [44]. In measuring the value of a short circuit current, the maximum current of the PV operation is calculated by a constant factor k, such as in the CV algorithm. The value of constant k is also different for various PV panels because it is dependent on the manufacturing of PV cell types. This method is improved by dynamically adjusting the value of k [45], which makes the method complex and difficult to implement. This method is very simple, but the tracking efficiency is very low.

B. *On-line Methods*

Online MPPT methods obtain the MPP by actually measuring voltage parameters and/or current in the system. These methods track the MPP based on a search algorithm. The MPP of the power curve is determined without interrupting system operation [37]. The real operation power point oscillates with a certain range around the actual maximum power point. Examples of online methods are P&O, IC, hill climbing, and parasitic capacitance.

1) *Perturbation and Observation Method*

The P&O method is the most popular online MPPT method. The MPP can be found by periodically increasing or decreasing the PV array current or voltage where the MPPT continuously seeks peak power operation [46]. Therefore, the subsequent perturbation should be maintained in the same direction at increasing power, to determine the MPP, whereas the perturbation should be reversed at decreasing power. This algorithm also works with instantaneous PV panel voltage and current. Oscillation usually occurs at the MPP after a single round of sampling in each switching cycle [47]. Oscillation can be minimized by reducing the perturbation step size. However, a smaller perturbation value will slow down the MPPT in reaching the MPP. The oscillation and time to reach the MPP is optimized by a variable perturbation size [48]. Taylor and Francis [49] reported an improved MPPT algorithm for PV systems, which produced no oscillation around the MPP, based on a combination of nonlinear and P&O methods.

2) *Incremental Conductance (IC)Method*

The IC method is based on the analysis of the PV array of the current/voltage slope (dI/dV), which is zero at the MPP, positive on the left of the MPP, and negative on the right of the MPP [5]. The increment size in this method determines the speed to reach the MPP. Fast tracking can be achieved by using bigger increments. However, the obtained power will become unstable at the MPP or oscillate around it.

3) *Hill Climbing Method*

Another method that is quite similar to the P&O is the hill climbing method, which decreases or increases the pulse width modulation (PWM) duty cycle by observing the effect on the PV output power. If the instant power is greater than the previously computed power, the online ion of perturbation is maintained. Otherwise it should be reversed [50]. A modified adaptive hill climbing method was developed by Xiao and Dunford [51]. The modifications on the conventional hill climbing method include automatic parameter tuning of the incremental step of switching duty cycle, and control mode switching to overcome the rapidly changing atmospheric conditions. The main problems in the hill climbing method are the oscillation around the MPP and MPPT failure under rapidly changing atmospheric conditions.

4) Parasitic Capacitance

Another method similar to the IC method is the parasitic capacitance algorithm, which models the charge storage in the P–N junction of a solar cell in terms of capacitance [11]. The parasitic capacitance method has better tracking speed and higher efficiency compared with the P&O and IC methods. However, this method is difficult to implement accurately because the capacitance of a solar cell should be determined experimentally by measuring the RC time-constant of the cell using a known value of resistance[5].

C. Artificial Intelligence Based MPPT Method

Artificial intelligence is used for improvement of the MPPT technique, either through offline or online methods. The improvements adapt or adjust the parameters of MPPT calculation. Accurate, robust, and flexible application is required for faster tracking.

1) Fuzzy Logic Controller

Fuzzy logic controller (FLC) was used recently to track the MPP of PV systems because this system has the advantages of robustness, simple design, and minimal requirement for accurate mathematical modelling [47, 52-54]. Fuzzy logic has improved the performance of P&O and hill climbing MPPT methods by optimizing the perturbation. The efficiency of energy harvesting from PV array was improved [55]. However, fuzzy logic methods strongly depends on the careful selection of parameters that define the membership function and the fuzzy rules table [8]. The development of fuzzy methods is also greatly influenced by expert knowledge and experimentation in selecting the parameters and membership functions.

2) Artificial neural Network

Several MPPT studies were conducted using ANN applications [56-58]. Most ANN-based methods require large amounts of field data on atmospheric conditions to train the ANN. An ANN-based MPPT was proposed in a related work, wherein an optimal instantaneous PV voltage factor was determined using a trained ANN [59]. ANN input includes temperature module and solar irradiation. However, the main problem of ANN-based methods is the need for in-depth data for training. Moreover, this method cannot be implemented for PV arrays with different characteristics.

3) Hybrid Artificial intelligent

Adaptive fuzzy logic control [60] and parameter optimization methods, such as genetic algorithm (GA) [61] and particle swam optimization [62-63], have been applied to existing MPPT algorithms to address the drawback of MPPTs that use the FLC method. Further improvements are required, especially for the optimization of the FLC membership function sub-sets. A new variant of intelligent technique was proposed to improve the fuzzy logic-based MPPT controller in a PV system [64]. Here, the FLC is integrated with the Hopfield neural network (HNN) to optimize the membership functions of the fuzzy logic system. Several applications of the HNN have been developed for various fields since Hopfield proposed the HNN model [65-66]. In solving optimization problems, the HNN has a well-demonstrated capability of finding solutions to complex tasks. The application of the HNN for solving optimization problems is based on the convergence of the energy function, which moves toward a minimum value based on the weight of coefficients [67-69].

A combined artificial intelligence of fuzzy logic and ANN for tracking MPP in PV systems can be found in [70-71]. In this method, the ANN is trained offline using experimental data to determine the reference voltage of the PV operation, which is the voltage at the MPP on the PV array characteristic. The reference voltage is compared to the instantaneous PV array voltage to generate a signal error. The signal error is then considered as input of the FLC. The FLC generates a duty cycle value for the PWM generator. The duty cycle value is then applied to the switching of the boost converter, which is connected to a PV array. However, this method requires plenty of data for offline training.

An improved ANN-based MPPT for stand-alone PV system is the GA-optimized ANN, which was proposed by Kulaksiz and Akkaya [72]. GA is used to select important data automatically among all ANN input. The algorithm requires any previous knowledge, and the process for obtaining the module parameters for data optimization is laborious. This ANN-based method improves the transitional state and reduces the oscillations in steady state because the MPP is obtained beforehand by the ANN model.

IV. TRENDS AND CHALLENGES

Most MPPT techniques obtain the maximum possible power of PVs by searching the localized maximum power. Various researchers have recently developed MPPT techniques to find the global MPP when partial array shading occurs. MPPT techniques should automatically respond to changes in the array that are due to aging and broken or open connection in the array circuit.

The P&O and IC methods are the most commonly used methods for MPPT techniques in PV system application. These methods can be easily applied in the real-time tracking of the PV array MPP operation. Both methods are easy to implement and do not require measurement of irradiance, temperature, short-circuit current, or open-circuit voltage. Some advanced methods, such as adaptive or improved P&O, fuzzy logic control, and Anfis, were developed based on P&O or IC methods.

The variances of P&O and IC methods are very competitive compared with those in other methods because they require simpler hardware for proper design optimization. These methods are very efficient because they only use current and voltage sensors during feedback generation.

Another trend in the development of MPPT techniques is the consideration for responses to irradiance and temperature changes; some responses are specifically more useful if temperature is approximately constant. The current MPPT techniques for PV application are tabulated in Table 1.

TABLE I. COMPARISON OF VARIOUS MPPT TECHNIQUES

MPPT Technique	Features							References
	Real MPP	Depend on determined PV array	Complex	Speed	Sensor Parameter	Adjustment periodic	Cost	
Curve-fitting	no	yes	medium	fast	irradiation, temperature	yes	medium	[40, 41]
Constant voltage PV	no	yes	simple	fast	voltage	yes	low	[37, 43]
Constant current PV	no	yes	simple	fast	current	yes	low	[45]
P&O	yes	no	simple	slow	voltage, current	no	medium	[49]
IC	yes	no	medium	slow	voltage, current	no	medium	[5]
Hill Climbing	yes	no	simple	slow	voltage, current	no	medium	[51]
Parasitic Capacitance	yes	no	high	medium	voltage, current	no	medium	[5, 11]
FLC	yes	no	medium	fast	voltage, current	no	low	[47, 52-54]
ANN	no	yes	high	fast	irradiation, temperature, current, voltage	yes	high	[56-58].
Hybrid AI	yes	yes	high	fast	irradiation, temperature, current, voltage	yes	high	[62, 63], [61], [64]

Some challenges exist in the development of MPPT in PV systems. The main challenges in the existing MPPT are efficiency, response speed, accuracy and flexibility of different PV cells, application, and the material or potential environmental condition. The details on the challenges in MPPT control strategy in PV systems is discussed in the next section for future research considerations.

The MPPT control strategy needs an appropriate balance of dynamic and static efficiency [34]. The MPPT control strategy requires robust static efficiency for slowly varying arrays. This efficiency can be achieved by a slow MPPT tracking approach that finds the maximum voltage/current and remains stable without too much movement from the current. The MPPT control strategy requires high dynamic efficiency for quickly varying arrays. This requirement can be achieved by a fast MPPT approach that can quickly find the new maximum voltage/current. This method requires more searching and will compromise static efficiency. Thus, MPPT efficiency above 99% is suggested, in lieu of the lack of standard for MPPT efficiency.

The MPPT control strategy should obtain the global maximum power when partial shading or broken parts of the PV panel is present. The global maximum power is required for searching all peak powers on the line curve at every condition. Several MPPTs are trapped at local maximum power when partial shading and broken part problems are present.

MPPT control strategies should not depend on certain PV panels to facilitate the flexible, compatible, and global function of overall PV panels. Moreover, the MPPT control strategies can be applied directly when the PV panel is constructed from various PV modules. This method will enable the MPPT to function without the data specification on PV cells, modules, or panels.

The MPPT control strategy should respond quickly to changes in ambient condition and to miscellaneous disturbances. This requirement tests the robustness and accuracy of MPPT. Ambient conditions or miscellaneous disturbances may be caused by a sudden change in irradiation or temperature, which result in the disruption of a PV panel. Flying objects, wind, or falling objects are some conditions that may cause sudden changes.

The MPPT controller should be simple enough to be implemented in hardware. The MPPT does not require several components and sensors, and it can be assembled in a small package. This requirement supports the power conditioner of the PV system. Power conditioner devices in PV systems are used to protect and control devices, such as the DC–AC converter, charge regulator, and inverter [15-16]. These devices process the electricity produced by a PV system to enable the system to meet the demands of the load. These devices also allow the PV generator to work as closely as possible to its maximum power point, thereby optimizing energy transfer and resulting in a more efficient system. Hence, MPPT is built in the power conditioners of PV system applications.

The development of MPPT controllers should be low-cost to reduce the investment in the PV system and to help increase the ROI of the user. The ROI can be enhanced via high harvest efficiency [34], which is the ability of the system to extract the maximum amount of power available from the PV panel.

V. CONCLUSION AND SUGGESTION

This paper reviewed the MPPT for PV systems. The concept of the PV systems was briefly discussed. PV systems are made up of a PV panel, power conditioner, and user or load. The PV power conditioner enhances the energy harvesting and interfacing property of the PV panel to load or to user voltage rating. The power extracting enhancement of PV operation is realized by MPPT. The DC–DC boost converter is usually used for MPPT media. The various MPPT techniques for PV system are grouped as offline, online, and intelligent methods.

Offline methods work by estimating the maximum power of PV operation based on the calculation of PV voltage at MPP via empirical data and mathematical expressions of numerical approximations. The advantage of these methods is their simple structure and low-cost application. However, they cannot exactly obtain the MPP as they only estimate the value of the MPP. These methods require a large database and large memory to develop the formulation. Moreover, they cannot follow changes in terms of contamination and aging of PV cells.

Online methods are also called real tracking methods. The advantages of these methods include the following: simple database or memory requirement for MPP determination, independence from the aging and other conditions of the PV cells, independence from ambient variation, and compatibility with multipurpose PV system applications. However, these methods require continuous reading of the voltage and current of the PV panel.

Intelligent methods are developed based on offline or online methods using fuzzy logic, neural network, and other artificial intelligence and natural philosophy methods. Intelligent methods improve system performance in terms of response speed, oscillation, and the effect of various conditions of the PV cells on the environment. The disadvantages of these methods are the costly and complex application.

Improvements on the current MPPT techniques are suggested for further research and development. Existing techniques can be improved by enhancing the versatility of various PV system applications, obtaining the global maximum under shadow conditions, simplifying the implementation, ensuring low development cost, and increasing the robustness and accuracy of MPP tracking.

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