A Critical Review of Various MPPT Methods of Solar PV System

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Abstract: *A well-organized maximum power point tracking (MPPT) method is vital for improving photovoltaic systems' performance. A comprehensive review of the classification of MPPT methods for PV systems is provided in this study. The methods are categorized into different groups based on their tracking ability. This study focuses on the salient features. The advantages and drawbacks, classification, and vast comparison of different methods given in this study can be used as a reference for further research to improve the performance of PV systems. The tabular representation is also used to improve the performance of tracking methods, which will assist in picking the suitable approach for any particular exercise.*

Key Words: MPP, PV, PSC, Temperature & Irradiance.

1. Introduction

Due to the increment in the greenhouse effect and decrease in conventional fuel availability, new energy sources are needed [1], [2]. Compared to other sources of energy solar energy is preferable due to its availability, it does not affect the environment, and it is easy to install the setup [3], [4]. The system's load can be satisfied with the PV source of electrical energy generation. However, the PV system is not the majority source of energy generation due to its high initial cost. Because the PV Systems' energy depends on various factors like environmental conditions, connected load, Sun Irradiance, and Temperature, constant power generation is difficult. For getting the maximum output from the PV module some reliable mechanism is needed, known as maximum power point tracking (MPPT). The MPPT enhances the efficiency and working time of the PV system [5], [6].

Scientists and researchers have done various work in the field of sustainable energy generation by the PV system. Due to this, a lot of MPPT algorithms are present in the literature for both off-grid and grid-associated PV systems [7]. However, the selection of a specific algorithm for any particular task is very difficult [8]. For example, the hill climbing (HC) [9] and perturbation and observation (P&O) methods are extensively used as MPPT algorithms because of their simple working and fewer requirements. The incremental conductance (INC) algorithm [10], which is used for incremental and quick conductance of PV systems, can track the maximum power point (MPP) of a PV system and transfer high PV power to the load. The confusion between P&O and INC methods has been clarified in the research paper [11], proving that both algorithms are almost highly uniform under steady-state and transient conditions. Besides ignoring the higher-order term in the discrete differentiation of the power both methods are almost the same. The sliding control (SC) method is more accurate but complex than ordinary methods [12]. The traditional methods, such as HC, P&O, fuzzy logic, INC, and neural networks, are not able to find the global MPP (GMPP) under partial shading conditions (PSC) [13]. The performance of meta-heuristic methods for finding global MPPT (GMPPT) is depicted in the paper [14]. It is seen that the GMPP convergence is achieved by particle swarm optimization (PSO) and Cuckoo search (CuS) methods, and the CuS technique's tracking ability is superior to the PSO. A model-free spline-guided Jaya algorithm [15] is used for the brilliant MPPT in the PV system, which is quicker in convergence and performs better under PSC. An economical and easy MPPT method based on temperature, which needs very few sensors is described in the paper [16]. The description of the bisection search theorem-based MPPT method is provided in the paper [17]. This method is particularly used when at least two neighborhood MPPs are present under different climate conditions.

Research works in the paper [2] have presented a categorized elaboration of different methods with 3 categories. Five parameters are used to compare the different MPPT algorithms with categorization in the paper [18]. Five categories are used for different MPPT methods in the paper [19] with five different parameters.

The arrangement for the rest of the paper is given as. The 2nd Section describes the PV module with its I-V & P-V curves and the effect of temperature, irradiance, and PSC on maximum power. The need for the MPPT controller, selection parameters, and Partial Shading condition (PSC)-enforced MPPT methods are given in the 3rd Section. A summary of different MPPT algorithms and their comparisons is denoted in the 4th Section. A generalized discussion of the reviewed methods is also given in the 4th Section. The conclusion is depicted in the 5th section.

2. PV Module

The equivalent PV module is presented in Figure 1 [1]. Where the photo-current is depicted as I_{ph} and PV current by I_{pv}, the generated PV voltage is given by V_{pv}. R_p and R_s are the parallel and series resistances. The diode's temperature voltage is V_t and the diode current is I_D.

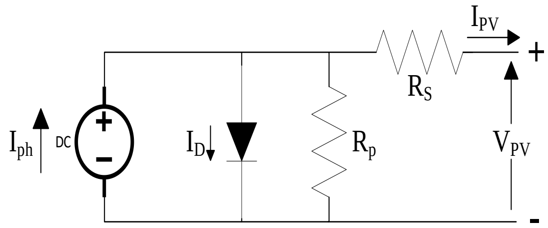

Figure 1: Equivalent Circuit of PV Module

The modeling of the PV system is categorized into 3 groups and system information is described by these categories.

2.1 I-V and P-V Characteristics

PV is formed with two separate words namely photo and voltaic, where the photo is used for illumination, and voltaic means the generation of power [20]. That means it is the process of generation of electrical power from solar energy, for this solar module is created with various solar cells. Solar cells contain p–n junction diodes fabricated in a thin layer of semiconductor [21]. This ideal module can give a complete understanding of the working of the PV system at different climatic conditions [18].

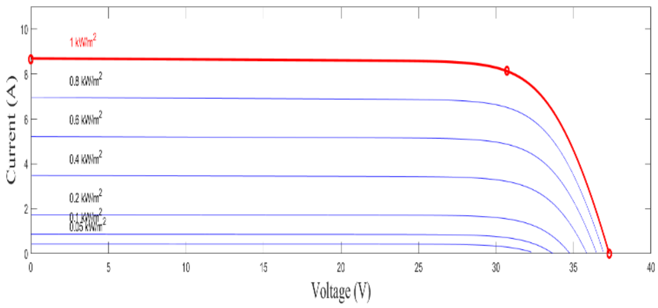

Figure 2: I-V Curve for the PV Module

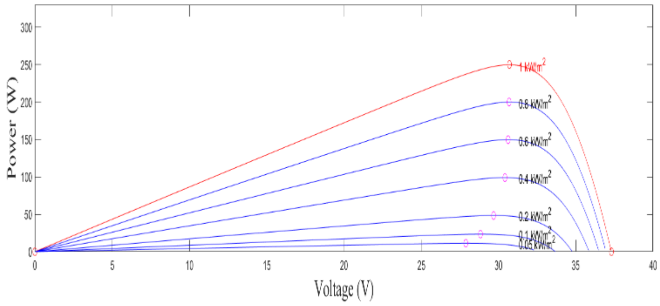

Figure 3: P-V Curve for the PV Module

2.2 Effect of Temperature and Irradiance

The PV result depends on the altering behavior of the climatic conditions [22], [23]. Since the insolation of the sun depends upon the angle made by sun rays, this parameter directly affects the $P - V$ and $I - V$ curves results [18]. The output current, I_{PV}, of a PV module, is highly affected by different sun-based irradiance levels, G, though the output voltage, V_{PV}, remains practically constant. In 2nd case, of a varying temperature, it is seen that the voltage changes normally while the current remains practically fixed [7].

The 3 reasons the temperature of the PV cell increases: (i) due to its temperature at the time of PV activity, (ii) the energy originated at the infrared level, which increases the temperature of the cell, and (iii) an increase in sun-oriented irradiance [8]. Equations (1) and (2) provide Open Circuit Voltage V_{OC}, and Short Circuit Current I_{SC}, of PV modules at different sun irradiance and temperature levels, where the unit of sun irradiance (insolation) is W/m^2.

$$V_{OC} = V'_{OC} + \alpha_2 * (T - T') - (I_{SC} - I'_{SC}) * R_S \quad (1)$$

$$I_{SC} = I'_{SC} * (G/G') + \alpha_1 * (T - T') \quad (2)$$

The current and voltage temperature coefficient is given by α_1 and α_2 in (1) and (2) [8], [24]. V'_{OC} and I'_{SC} are the open circuit voltage and short circuit current at the reference solar irradiance G' and temperature T'.

The photo-current is depicted as I_{ph}, and afterward the PV module short circuit current depends upon the temperature and irradiance, which advocates that due to sun radiation, the current changes and power increases and reaches the maximum value [25], [26]. To detect this, the MPPT is used to find the MPP with the changing temperature and irradiance.

2.3 Effect of Partial Shading Condition

Besides irradiance and temperature, partial shading also has a significant effect on PV system characteristics [27],

[28]. The Partial Shading Condition is known as the different situations in which different parts of a PV module get uncommon values of irradiation. The reason for shading could be the effect of mists, contiguous structures, and trees [29]. By this, we can understand that the working of PV under PSC is the most important aspect to consider. In a PV system, at the time of shading condition, the PV panel receives low or no insolation, due to which the photo-current (I_{ph}) of the module decreases. As per Kirchhoff's current law, the current of all series connected loads must be the same, by this principle the current of all series connected cells will be the same, and the magnitude of the photo-current will reduce due to shading conditions and for compensating this decrement of photo-current, the diode will work in the breakdown region. Thus, the shaded PV cell will work as a load in place of a generator [29].

3. MPPT Controllers

The process of extracting the maximum power from the PV system is called the maximum power point tracking and the tool used for this process is known as the MPPT controller. If there is no effect of environmental conditions then the MPPT controller will provide the maximum power by enhancing the efficiency of the PV system. This can be achieved by adjusting the load connected to the PV system at different climate conditions. Two processes are used to extract the maximum power from the PV system namely electrical and mechanical tracking. Different directions of PV panels are used in mechanical tracking according to the variations in climate conditions in different months for a whole year, On the other hand, the I-V curve is used to determine the location of MPP in electrical tracking [8], [30], [31]. In electrical power generation from PV modules, MPPT is an important factor, that provides maximum power to different types of loads. Since the generation of electrical power from sun energy through PV modules is still poor and the variation in irradiance is a vital issue, due to these problems the MPPT becomes an important application to use.

3.1 Need for MPPT Controller

The variation in climate conditions affects the power production from a constant power source and the impact is more vital in PV and wind energy systems. These sources face different problems like varying environmental conditions and grid synchronization [2], [32]. That's why, MPPT is used in solar PV and wind energy systems to generate power [33], [34]. Due to this MPP is important in I-V and P-V curves. With the variation in climate conditions, the location of MPP regularly changes and MPPT controllers are well designed to locate the changing MPP. For this, the MPPT controller varies the resistance of the PV module[32].

3.2 Parameters for Picking the MPPT Controller

In the PV system, various methods have been used for processing the application of MPPT as depicted in several research literature. The parameters of MPPT needed for the controlling are the criterion for selecting an appropriate technique. The parameters of selection give the required knowledge about which technique is superior for a specific task. The classification of the various algorithms is not possible with these selection parameters because these are used only for making comparisons among the various techniques in one group. For comparing the various techniques of each group 11 selection parameters are used here. These are depicted in Table 1 [35]–[37] and a comparison based on the speed of operation among generally used analog or digital maximum power point tracking ICs or microcontrollers is given in Table 2.

3.3 MPPT Controller under PSC

Techniques that work at constant irradiation and under PSC are depicted in Table 3. It is analyzed that complex and digital techniques are needed under PSC for high accuracy and big calculations. As per analysis, it is seen that regarding convergence speed, PV module reliance, sensitivity, and periodic tuning the particle swarm optimization, genetic algorithm, PV output senseless, biological swarm chasing, differential evolution, soft computing, ant colony optimization, and firefly algorithm executes better under PSC than the other conventional methods because the conventional techniques are not able to find the global maximum power point precisely under partial shading conditions, that's why the GMPPT algorithm is required [38]. Theoretically, the GMPPT algorithm is divided into two groups [39], [40] namely hardware architecture-based and firmware-based algorithms, but these techniques are not suitable for the tracking of maximum power points in a varying system is not suitable because severe oscillations get near the GMPP. To overcome these difficulties, the method used is described as a hybrid grey wolf optimizer (GWO)–fuzzy logic control (FLC) algorithm given in the article [41], which is suitable for tracking variable GMPP. The global perturbed-based extremum seeking (GPESC) method is depicted in the paper [40] and it gives 99.99% accuracy while tracking the GMPP at both constant and varying photovoltaic patterns.

4. Review of Various MPPT Methods

With the brilliant adaptability of photovoltaic power, researchers tried too much to achieve the maximum power from the PV panel. On that day, many MPPT methods have been evolved. Each method has its operating procedure, advantages, losses, and uses.

Table 1: Description of several selection parameters of MPPT controllers

Selection Parameters	Descriptions
Arrangement Difficulties	For an accurate and efficient algorithm, the complexities of design are a must to consider. Users always choose a quiet and easy-to-process technique rather than a difficult one. That's why, this selection parameter is important while picking a suitable MPPT method.
Tracking real MPP	Partial shading conditions can affect the natural operation of the MPPT in PV panels. The tracking process is affected by the variation in the P-V characteristic curve of the PV system [1]. Therefore, the MPPT controller should work properly while tracking the real MPP.
Expenditure	The need for different specific parts for numerous purposes in the tracking of MPP by an MPPT controller increases the tracking cost [35]. So the cost of the system is important to consider when preparing the MPPT controller of the PV module.
Faith in the PV module	Many algorithms and numerical techniques can track the MPP without having proper information about the PV module but some algorithms like fuzzy logic controllers and artificial neural networks are dependent on the size and structure of the PV module.
Initial Training	The Artificial Neural Network, look-up table Technique, and some other algorithms need initial training before the implementation of these techniques. The fuzzy logic controller needs initial information before the manufacturing of the MPPT [35].
Speed of Conversion	The Speed of conversion should be high however the PV system has variable MPP due to changing temperature and irradiance. To minimize the losses, the speed of conversion of the PV system should be at the proper intensity.
Analog or Automated	In maximum power point tracking both analog and digital commands can be used, some examples of this type of operation are fractional short circuit current and open circuit voltage technique. Digital methods are more accurate but expensive as compared to analog techniques.
Parameters of Sensing	An MPPT controller is not completed without the voltage and current sensors. The voltage sensors are more compact and economical than current sensors. So that these points should be addressed at the time of manufacturing of MPPT.
Adjustment of Period	The variation in temperature and environmental conditions affect the output of the MPPT controller as it reduces over time. Consequently, periodic tuning is a factor to look up by some means [35].
Consistency	The conventional methods are not able to operate in stable conditions, due to which the output affects very much so that the method operation should be as stable as it could be.
Efficiency	The MPPT controller should be efficient to ensure the steady-state operation of the PV system [37]. This specification is one of the crucial parameters for picking a suitable MPPT controller.

Table 2: Comparison among generally used analog or digital MPPT ICs or Micro-Controllers [36]

ICs or Micro-controllers	Speed of Tracking	Utilized in MPPT Techniques
analog circuitry	20 ms	Electronic Support Measure
DSP TMS320F240	20 ms	P&O-dependent Proportional Integral
DSP TMS320F28335	1.5 s	Fuzzy Logic Control-dependent P&O
DSP TMSF28335	80 ms	Load-current dependent MPPT
FPGA Vertex II	30 ms	Adaptive Neuro Fuzzy Interference System
FPGA XC2C384	85 ms	Perturb & Observe
microcontroller Intel 87196	500 ms	Incremental Conductance
PC PENTIUM IV 2.4 GHz	16 ms	Incremental Conductance

Table 3: Some well-recognized MPPT Techniques under PSC and Uniform Irradiation condition

Under Uniform Irradiance Condition	Under PSC	
i. Perturb & Observe (P&O)	i. Particle Swarm Optimization (PSO)	xi. Beta Algorithm
ii. Hill Climbing (HC)	ii. Genetic Algorithm (GA)	xii. Sliding Control (SC)
iii. Incremental Conductance (INC)	iii. Differential Evolution (DE)	xiii. Cuckoo search (CuS)
iv. Open Circuit Voltage (OCV)	iv. Artificial Neural Network (ANN)	xiv. Firefly Algorithm (FA)
v. short circuit current (SCC)	v. Fuzzy Logic Control (FLC)	xv. Artificial Bee Colony (ABC)
vi. Ripple Correlation Control (RCC)	vi. Back Stepping Controller (BSC)	xvi. Ant Colony Optimize (ACO)
vii. Current Sweep (CS)	vii. PV Output Senseless (POS)	xvii. Sine-Cosine Optimization (SCO)
viii. DC Link Capacitor Droop Control	viii. State-Based (SB)	—
ix. Load I and V Maximization	ix. Array Reconfiguration (AR)	—
x. dP/dV or dP/dI Feedback Control	x. Parasitic Capacitance (PC)	—

4.2 Discussion of Findings

Researchers and scientists all over the globe have been trying for a very long time to enhance the efficiency of the solar module and the MPPT is the most important exercise to take on many researchers. Several new MPPT methods have been already developed to extract maximum power from the PV module. Picking a specific MPPT method for a Particular application among the existing methods is a difficult task as each method has its pros and cons. In this review work, a comprehensive review of different MPPT methods is presented from different works of literature along with their merits and demerits. After reviewing the research works on the discussed MPPT methods of the solar PV system, the following discussion can be made, which may be a piece of useful equipment for picking the most constructive and suitable type of MPPT method to fulfill the needs of both operators and consumers.

- Conventional methods such as P&O, INC, and HC are simple since their circuit of implementation is not complex, but they have less accuracy, and tardy in response, and show a problem of oscillations near the MPP under changing climate conditions. In this study, the modifications to these conventional methods are also discussed, which express some improvements to these methods.
- Among the methods discussed, for degraded and lower ripple voltage, better transient response, quick change of irradiation, and less difficulty of implementation, the β method can be an exciting solution for extracting much power from the energy source.
- Huge computation is needed for the gradient descent-based technique which increases its difficulty and shows less tracking accuracy under PSC.
- Under PSC, the evolutionary techniques are the most precious for extracting the best amount of power from the PV modules. Among EA methods, the Particle Swarm Optimization method with a similar structure to HC is found to be a valuable one.
- Besides evolutionary and intelligent prediction methods, like Particle Swarm Optimization, Differential Equation, Genetic Algorithm, FLC, and Artificial Neural Networks, SC, FA, and POS give pre-eminent features under PSC than the other conventional MPPT methods.
- Among the GMPPT algorithms, the global perturbed-based extremum-seeking (GPESC) scheme performs better in tracking the GMPP for both static and dynamic PV modules.
- The constant parameter-based methods like Constant Voltage, Constant Current, SCC, and OCV, are quicker since they don't need the calculation of derivatives.
- The current-based methods require costly and complex hardware for implementation, which causes more losses than the voltage-based method; however, it is more accurate than the voltage-based one.
- BSM is a more suitable method in terms of simple hardware execution, no requirement to compute derivatives, is economical, has fewer sensor needs, and has quicker tracking accuracy.
- Among the methods based on measurement and comparison, the transient-based method is much better because of not contain the energy buffer stage (DC/DC) and is not based on continuous perturbation.
- The numerical-based methods, like Newton Raphson, false position, Sliding Mode, Brent Method, etc. solve the problems of stability, tracking accuracy, and speed that are faced in conventional methods.
- Intelligent prediction methods such as Fuzzy Logic Control, Artificial Neural Networks, or ANFIS can handle non-linearity without an accurate mathematical model and provide evident tracking efficiency. They have some issues as they are expensive but can be a piece of excellent equipment for extracting maximum power from the PV sources.
- The field programmable gate array (FPGA) Vertex II, digital signal processor (DSP) TMS320F240, and PC PENTIUM IV 2.4 GHz micro-controllers are the most promising ones for implementing the digital MPPT controller as they have faster tracking performance than the other micro-controllers.

5. Conclusion

Renewable energy efficiency fully depends on the performance of solar modules by extracting the maximum power. For this, the MPPT can be used to achieve the maximum power delivered by the photovoltaic module. Various articles have been proposed to achieve the condition of maximum power using different algorithms. Detailed information about various methods has been given in this article with their different aspects alongside achieving the suitable method for a particular situation. A tabular comparison is provided, which may be a bizarre apparatus for the subservience of picking the most fertile and perfect MPPT to satisfy the different conditions of both operators and consumers. This Article will provide pleasant information to work in this sector for improving the performance of the solar modules.

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