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Analysis of Maximum Power Point Tracking (MPPT) Techniques under Different Atmospheric Conditions: Technical Review

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ABSTRACT

The use of solar photovoltaic (PV) a renewable energy technology is on the rise. However, it has challenges. It has high initial cost and low energy conversion efficiency. It produces variable power that depends on atmospheric conditions that involve uniform radiation, rapidly varying radiations, temperature variations and partial shading conditions (PSCs). Further, it produces maximum power only at the maximum power point (MPP). The MPP characteristics under the different atmospheric conditions are divergent. In addition, the MPP varies continuously as the atmospheric conditions changes and it not the same as the operating point. Hence, Maximum power point tracking (MPPT) techniques is required to extract the maximum power produced whatever the atmospheric and load conditions. This work studied the effect of different atmospheric conditions and the load on the MPP. It examined the performance of MPPT techniques under different atmospheric conditions. The study reviewed published literature on MPPT techniques covering the three broad classifications of offline, online and hybrid MPPT techniques. The online MPPT techniques consist of Conventional, Artificial intelligence, and Emerging or nature inspired MPPT techniques. The study showed that MPPT techniques have been developed that considered tracking MPP under uniform radiation and PSCs, very few under rapidly varying radiations and almost negligible under temperature variations. The study showed that offline and conventional MPPT techniques fail to track MPP under rapidly varying and PSCs, however, Artificial intelligence and Emerging MPPT techniques could track MPP under PSCs. Moreover, oscillations about MPP occur amongst some MPPT techniques.

Keywords: *Atmospheric conditions, Maximum power point (MPP), MPPT Techniques, Partial shading conditions (PSCs).*

1 INTRODUCTION

The use of solar photovoltaic (PV) a renewable energy technology is on the rise. Solar PV is a technology that converts sunlight directly into direct current electricity by the photovoltaic effect using the solar cell. The solar cell is the basic unit of the PV system, is a large area P-N junction semiconductor device that is manufactured from mainly silicon and other conductive materials (Timmons et al., 2014).

Solar PV is modular. It does not produce pollution or green gas emission, it has long life span, and it has low maintenance with absence of moving parts. It does not require fuel to produce power. It produces power instantly (Sace, 2010). Despite these benefits, solar power has challenges.

The challenges of solar PV include high initial installation cost. It has low energy conversion efficiency that ranges from 6% to 20% (Green et al., 2015) this depends on the type of material used in the fabrication of the solar cell. Additionally, solar PV produces variable power that depends on irradiance and temperature that in turn are dependent on atmospheric conditions that involve uniform radiation, rapidly varying radiations, temperature variations and partial shading conditions (PSCs) (Berrera *et al.*, 2009; Sreekanth and Raglend, 2012). Likewise, solar PV has nonlinear characteristics, and it produces maximum power only at the maximum power point (MPP). The MPP varies continuously as the atmospheric conditions changes, and its characteristics are divergent under the different atmospheric conditions. Furthermore, the MPP and the load operating point are not the same.

The above challenges signpost that it is vital to extract the maximum power produced at all times whatever the atmospheric and load conditions. Achieving this requires locating and operating the solar PV at the MPP at all times. This essential but challenging task is performed by Maximum power point tracking (MPPT) techniques. The MPPT track the MPP, and at MPP, it uses the duty cycle to affect maximum power transfer to the load. MPPT techniques improve the efficiency of the PV system and are of economic benefit.

Because of the significance of MPPT techniques, this study investigated the effect of different atmospheric conditions and the load on the maximum power point (MPP). In addition, the study examined the existing MPPT techniques to ascertain their performance under the different atmospheric conditions.

The study reviewed published literature on MPPT techniques covering the three broad classifications of offline, online and hybrid MPPT techniques. The online MPPT techniques consist of conventional, artificial intelligence, and emerging or nature inspired MPPT techniques

The rest of the paper is arranged as follows. Section 2 presents the solar PV model and its characteristics, and it describes the effects of different atmospheric conditions and load on maximum power point (MPP). The section also gives a brief description and review of the MPPT techniques used in the study. Section 3 presents the results and discussions. Section 4 presents the conclusion.

2 METHODOLOGY

This section presents the solar PV model and its characteristics, and it describes the effects of different atmospheric conditions and load on maximum power point (MPP). The section also gives a brief description and review of the MPPT techniques used in the study.

2.1 SOLAR CELL MODEL AND EFFECT OF DIFFERENT ATMOSPHERIC CONDITIONS AND LOAD ON MAXIMUM POWER POINT (MPP)

This section presents the solar PV model and its characteristics, and it describes the effects of different atmospheric conditions and load on maximum power point (MPP).

1. SOLAR CELL CHARACTERISTICS

The solar cell is modeled as a current source in parallel with a diode, shunt resistance and series resistance this is as shown in Figure 1. The current source represents the photo-generated current that depends on the solar radiation and temperature, the diode represents the p-n junction area of the solar cell, the shunt resistance represents the leakage current, and the series resistance represents the internal resistance to the current flow. In this work, the single model is considered.

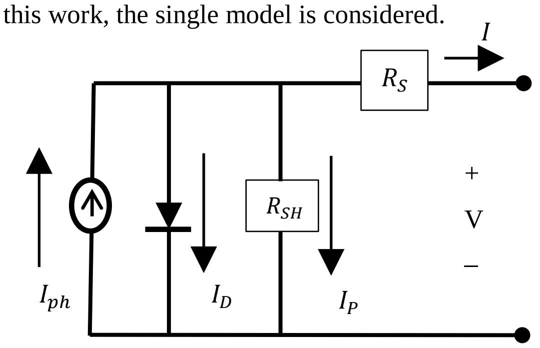


Figure 1: Simplified Equivalent Circuit Model for a Photovoltaic Cell

The current source which represents the photo-generated current that depends on the solar radiation and temperature, is given as in equation (1)

$$I_{ph} = \frac{G}{G_{ref}}\left[I_{sc} + K_i(T - T_{ref})\right] \quad (1)$$

where,

I_{ph} is the photocurrent at standard test condition (STC), I_{sc} is the cell short-circuit current at reference temperature and radiation, K_i is the short circuit current temperature coefficient, G is irradiance (W/m^2), G_{ref} is the solar radiation in 1000 W/m^2 at standard test conditions (STC), T is temperature (K), T_{ref} = 25 ℃ and Air mass (AM) = 1.5. All of these parameters are supplied by the manufacturer specifications.

Similarly based on the model the voltage-current (V-I) characteristic equation of a solar cell is given as in equation (2)

$$I = I_{ph} - I_o\left[\exp\left(\frac{q.(V+I\cdot R_S)}{nKT}\right) - 1\right] - \left[\frac{V+I\cdot R_S}{R_{SH}}\right] \quad (2)$$

where,

I is the Cell current, V is the cell voltage, I_{ph} is the light-generated current or photocurrent, I_o is the is the Reverse saturation current, R_S is the series resistance, R_{SH} is the shunt resistance, n is ideality factor, K is Boltzmann's constant, T is the cell's working temperature, q is electron charge.

As is often the case, $I_{ph} \approx I_{sc}$ therefore equation (2) is expressed as shown in equation (3)

$$I = I_{sc} - I_o\left[\exp\left(\frac{q.(V+I\cdot R_S)}{nKT}\right) - 1\right] - \left[\frac{V+I\cdot R_S}{R_{SH}}\right] \quad (3)$$

Further, I_o the cell saturation current varies with temperature according to equation (4)

$$I_o = I_{rr}\left[\frac{T}{T_{ref}}\right]^3 exp\left(\frac{qE_G}{KA}\left[\frac{1}{T_{ref}} - \frac{1}{T}\right]\right) \quad (4)$$

where,

T is the cell working temperature, T_{ref} is the cell reference temperature, I_{rr} is the cell reverse saturation temperature atT_{ref}, E_G is the band gap of the semiconductor used in the cell.

Subsequently, based on equation (3) the typical I-V, P-V characteristic curve for the solar cell/module/array is determined as shown in Figure 2. In addition, based on Figure 2 the important parameters widely used to describe the cell electrical performance are the open-circuit voltage V_{oc} , the short-circuit current I_{sc} , current at maximum power point I_{mpp}, voltage at maximum power point V_{mpp}, and power at maximum power point P_{mpp}.

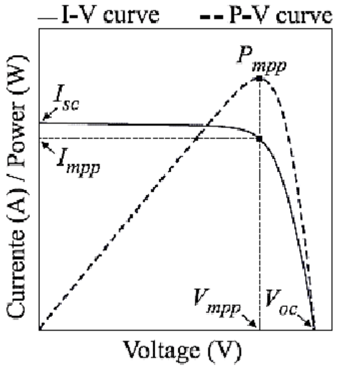


Figure 2: I-V and P-V characteristics important performance parameters

The short circuit current I_{sc} corresponds to the short circuit condition when the impedance is low and is calculated when the voltage equals zero that is I (at V=0) = I_{sc} . Moreover, the open circuit voltage (V_{oc}) is described by equation (5), it occurs when there is no current passing through the cell that is V (at I=0) =V_{OC}.

$$V_{oc} = \frac{nKT}{q} ln\left[\frac{I_{sc}}{I_o} + 1\right] \quad (5)$$

where, I_{sc}, I_o, n, K, T, and q retain the same meaning.

Further, P_{mpp} the power at maximum power point is given by equation (6)

$$P_{mpp} = V_{mpp} I_{mpp} = \gamma V_{mpp} I_{mpp} \quad (6)$$

where

V_{mpp} is terminal voltage of PV module at maximum power point (MPP), I_{mpp} is output current of PV module at maximum power point (MPP), γ is the cell fill factor, which is a measure of the quality of the cell and it is given by equation (7).

$$\text{Fill factor } \gamma = \frac{I_{mpp} V_{mpp}}{I_{sc} V_{oc}} \quad (7)$$

2. EFFECT OF DIFFERENT ATMOSPHERIC CONDITIONS AND LOAD ON MAXIMUM POWER POINT (MPP)

A brief description of the effect of different atmospheric conditions and load on maximum power point (MPP) now follows.

Under uniform radiation and under uniform illumination at constant temperature, change in solar irradiance is proportional to change in the photocurrent as expressed in equation (1). The change in irradiance has more effect on the short circuit current and minimal effect on open circuit voltage as shown in Figure 3. Moreover, increase or decrease in irradiance translates to increase or decrease in maximum power produced, and the MPP under this condition is mono as shown in Figure 4. Tracking the MPP is less cumbersome. However, the case is different under temperature variations.

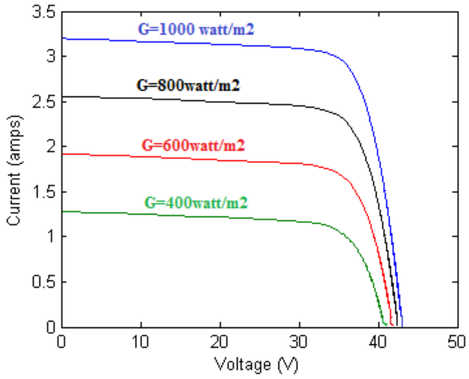


Figure 3: Irradiance and I-V characteristics

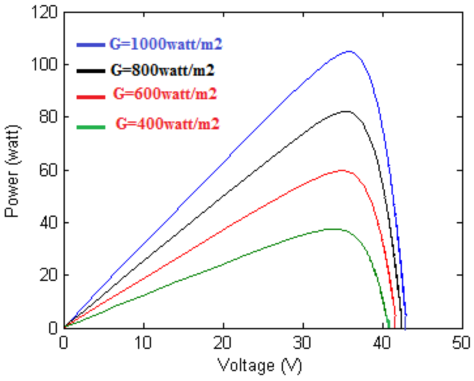
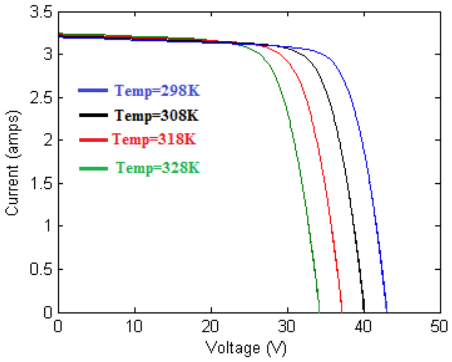
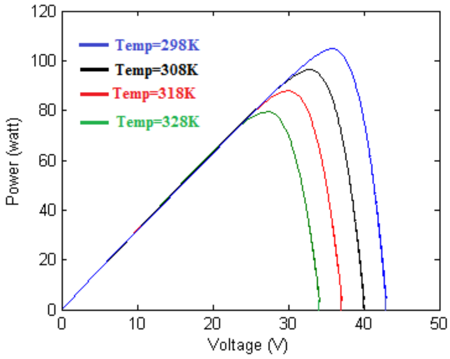


Figure 4: Irradiance and P-V characteristics

Under temperature variations, increase in temperature results in reduction of output voltage as shown in Figure 5(a) and as expressed in equation (4) and equation (5), where I_o the diode saturation current increases with rise in temperature. Conversely, rise in temperature has marginal increase in current as shown in Figure 5(a) and as expressed in equation (1). Overall, increase in temperature results to decrease in the maximum power produced while decrease in temperature results to increase in maximum power produced, this is as shown in Figure 5(b). The MPP is mono. Yet the case is different under rapidly varying radiations.



(a) I-V characteristics for 25°C, 35°C, 45°C, and 55°C



(b) P-V characteristics for 25℃, 35℃, 45℃, and 55℃

Figure 5: Temperature variations and the I-V and P-V characteristics

Under rapidly varying radiations, because the radiation changes abruptly, the maximum power point changes abruptly too, it is erratic. As such tracking the MPP has its own peculiar challenge. Nevertheless, the MPP is still mono. In contrast, under partial shading conditions (PSCs) the MPP characteristics is at variant to the others conditions earlier discussed.

Partial shading conditions (PSCs) results when part of the surface of the cell or module or array is shaded from direct illumination, from clouds, buildings, trees, leaves, or pollution. Shading reduces the output current, as it is directly proportional to the irradiance on the illuminated area of the cell as indicated in equation (1), but the output voltage is unchanged. Because of bypass diode added to protect the module against damage, the characteristics curve then becomes complex, the current –voltage curve appears as staircase this is as shown in Figure 6. Also, the power- voltage curve shows multiple maximum power points, however, only one of them is the global maximum power point (GMPP) this is as shown in Figure 6 (Liu, Y. H., Chen, J. H., & Huang, J. W. , 2015).

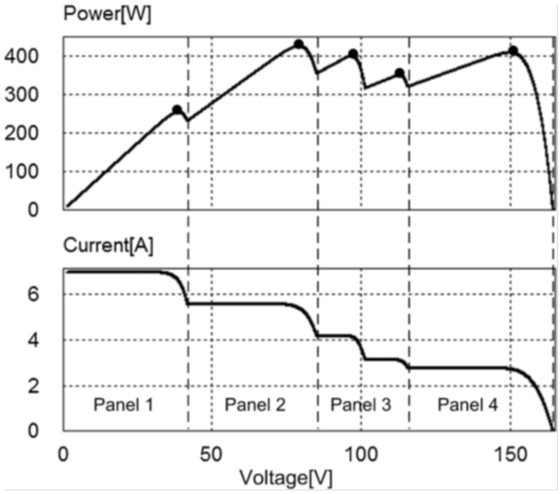


Figure 6: PV array under partial shading Daraban, et al., 2014)

In addition, partial shading cause losses in system output power, hot spot effects, and system safety and reliability problems (Kazmi *et al.*, 2009; Kotak and Tyagi, 2013). Thus, under partial shading conditions (PSCs), the MPP is not mono but multiple peaks, this creates a challenge in tracking.

In the case of the load, the operating point is different from MPP, therefore, the use of a dynamic impedance matching network whatever atmospheric and load conditions is vital to carry out transfer of maximum power to the load at the MPP. The MPPT techniques perform this task.

2.2 MAXIMUM POWER POINTS TRACKING (MPPT) TECHNIQUES

Maximum power point tracking (MPPT) tracks and locate the MPP whatever the atmospheric conditions, and at the MPP, it simultaneously transfers the maximum power to the load. The MPPT techniques consist of the tracking and control unit and the DC-DC converter, and the typical block diagram is as shown in Figure 7.

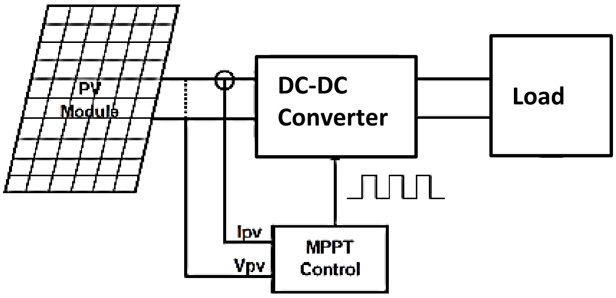


Figure 7: Typical block diagram of MPPT in a PV System

The tracking and control unit track and locate the MPP, at the same time it uses either maximum power point voltage V_{mpp} or current I_{mpp} as indicated in Figure 2, to set the duty cycle that is used to switch on and off the DC-DC converter. However, the voltage at MPP V_{mpp} is mostly used. The DC-DC converter then performs the transfer of maximum power to the load. Many different tracking algorithms are used. Likewise, different DC-DC topologies are also used depending upon the specific requirements.

Many MPPT techniques have been proposed and some implemented by researchers. These techniques differ in many characteristics such as required sensors, cost, complexity, convergence speed, range of effectiveness, correct tracking when irradiation and or change in temperature, hardware needed for the implementation or popularity.

Several authors have classified the MPPT techniques differently. However, in this work we adopt the broad classifications of offline MPPT techniques, online MPPT techniques and hybrid MPPT techniques. Besides, the online MPPT techniques include conventional MPPT techniques, artificial intelligence and emerging or natured inspired MPPT techniques.

1. OFFLINE MPPT TECHNIQUES

Offline method uses reference signal such as open circuit voltage (Voc), short circuit current (Isc), solar insolation, and temperature which is used to generate the control signal to track MPP. The offline MPPT techniques appraised include Fractional open circuit voltage (FOCV), Fractional short circuit current (FSCC), Curve fitting (CF) methods, and Look up table (LUT) methods.

A brief description of these offline MPPT techniques now follows. The Fractional open circuit voltage (FOCV), is based on the premise the open circuit voltage V_{oc} varies with the irradiance and temperature. The FOCV uses the linear relationship between voltage at MPP and the open circuit voltage as expressed in equation (8).

$$V_{mpp} = K_1 V_{oc} \tag{8}$$

where K_1 is a constant depending on the characteristics of the PV array, it ranges between (0.71 and 0.78). In the method the open circuit voltage V_{oc} is measured periodically, this leads to temporary power loss. This method only gives an approximation not the true MPP. The method fails to track MPP under rapidly varying, temperature variations and PSCs (Logeswaran, and SenthilKumar, 2014).

The Fractional short circuit current (FSCC) is similar to the fractional open circuit voltage method. The short current $\boldsymbol{I_{sc}}$ and current at maximum power point (MPP) I_{mpp} are linearly related as shown in equation (9).

$$I_{mpp} = K_2 I_{sc} \tag{9}$$

The coefficient of proportionality $\boldsymbol{K_2}$ is determined for each PV array, and it ranges between 0.78 and 0.92. However, measurement of the short circuit current while the system is operating is a problem. In addition, this method fails to track MPP under rapidly varying, temperature variations and partial shading conditions (PSCs) (Logeswaran, and SenthilKumar, 2014).

The Curve fitting (CF) method requires prior knowledge of PV technical data, panel characteristics, mathematical model and equation to calculate the PV array output in terms of the voltage corresponding to the MPP. It performs large number of calculations that slows it down. Likewise, it requires large memory. Besides, it fails to track MPP under rapidly varying radiations and partial shading conditions (PSCs).

The Look up table (LUT) methods depends on stored data from previous knowledge of PV panel characteristics and technical data. For varying atmospheric conditions, the system becomes complex, making the system slow. In addition, because not all possible scenarios could be predicted, the system is prone to fail when it meets conditions that are not stored. In addition, because it is offline, it fails to track MPP under PSCs.

2. ONLINE MPPT TECHNIQUES

Online techniques are independent from prior knowledge of PV modules characteristics. In this method, usually the instantaneous values of the PV output current and voltage are used to generate the control signal that is applied to the PV system. The Online MPPT techniques include conventional techniques, Artificial Intelligence techniques and Emerging or nature inspired techniques. Brief description of the online techniques now follows.

The conventional MPPT techniques methods are based on hill-climbing principle that consists of moving the operation point of the photovoltaic (PV) array in the direction in which power increase, and if power decreases the operation, point is moved in the other direction. Two popular MPPT techniques based on the hill-climbing principle are Perturb and Observe (P&O) and Incremental Conductance (Icond) MPPT methods.

In P&O method, the MPPT algorithm is based on the calculation of the PV output power and observing the change in power by sampling both the PV array current and voltage. The technique operates by periodically incrementing or decrementing the solar array voltage (Atallah, *et al.*, 2014). The algorithm for this technique is shown in figure 8.

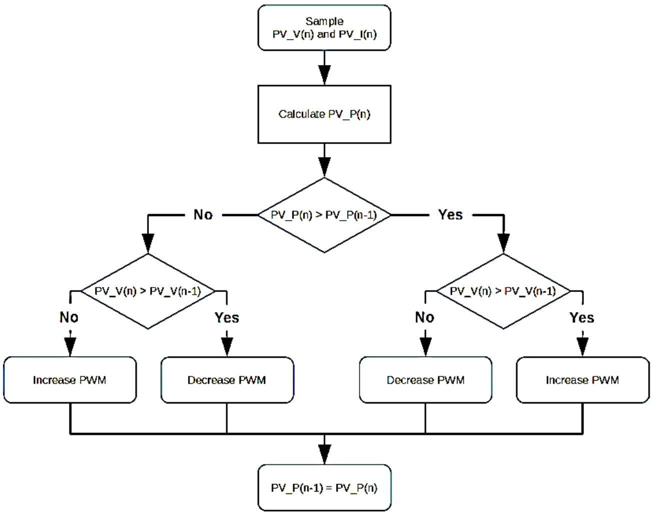


Figure 8: Flow chart of P&O Algorithm

If a given perturbation leads to increase in power, then the subsequent perturbation is generated in the same direction and vice versa. The duty cycle of the DC converter is varied and the process is repeated until the maximum power point has been reached.

A shortcoming of this method is that the system oscillates about the MPP. The technique never actually tracks the real MPP. In addition, reducing the perturbation step size can minimize the oscillation. However, small step size slows down the MPPT. For different values of irradiance and cell temperatures, the PV array would exhibit different characteristic curves. Additionally, apart from the oscillations around the MPP, the P& O can get lost and track the MPP in the wrong direction during rapidly changing atmospheric conditions. In addition, the

P&O fails to track the Global maximum power point (G_{MPP}) under partial shading condtions because there are multiple maxima in the curve (Logeswaran, and SenthilKumar, 2014).

The incremental conductance (Icond) MPPT uses equations (9) – (12) to arrive at the MPP.

$dP/dV = d(IV)/dV = \mathrm{I} + \mathrm{V}dI/dV = 0$
(9)

$dI/dV = -I/V$ At MPP (10)

$dI/dV >= -I/V$ At left of MPP (11)

$dI/dV <= -I/V$ At right of MPP (12)

where V and I are PV array output current and voltage respectively, the left hand side of equations represents Incremental conductance of PV module and the right hand side represents the instantaneous conductance. It is obvious that when the ratio of change in the output conductance is equal to the negative output conductance, solar array will operate at the maximum power point as shown in equation (10). By comparing the conductance at each sampling time, the MPPT will track the maximum power of the PV module. However, the speed of tracking depends on the size of the increment of the reference voltage. In addition, one drawback of this method is that it cannot differentiate between rapidly changing radiations.

Additionally, under partial shading conditions this method fails to track (G_{MPP}) (Logeswaran, and SenthilKumar, 2014).

Conversely, artificial intelligence techniques use complex mathematical models that involve the use of high computational efforts to obtain results. Hence, the system modeling allows the determination of the MPP with high accuracy. Some MPPT techniques under this category include Differential evolution (DE), Genetic algorithm (GA), Artificial neural network (ANN), and Fuzzy logic controller (FLC). The brief description of these techniques is discussed next.

Differential evolution (DE) requires a few parameters in the algorithm. A population of particles is required in DE and a few iterations are needed in order to generate the final solution. The differences in the particles are used to mutate each other in every iteration. The process starts with initialization of initial population of target vectors within the boundary constraints. The population vector of this system could be the reference voltage or current or duty cycle. DE technique could track MPP under PSCs (Tajuddin, *et al*., 2013).

The genetic algorithms are a family of computational models inspired by evolution. They are parallel global probabilistic search techniques based on the principle of population genetics. These algorithms encode a potential solution to a specific problem on a single chromosome and apply recombination operators to them to preserve critical information. The GA MPPT technique oscillates about MPP under PSCs (Daraban, et al., 2014).

The Artificial neural network techniques involve the use of a multi-layer feed-forward neural network (MFFNN) to track the MPP. The network consists of three layers: input layer, hidden layer and output layer. The number of neurons in hidden layer is determined by trial and error. The input variables can be the PV array parameters like V_{oc} and I_{sc}, atmospheric data like irradiance and temperature, or any combination of these. The output is usually one or several reference signals like a duty cycle signal used to drive the power converter to operate at or close to the MPP. The ANN MPPT technique could track MPP under PSCs. but it has to trained (Messalti, *et al.*, 2017) and it specific for that module or array.

The Fuzzy logic controller uses fuzzy logic to make decisions and control the output of the controller. The main components in fuzzy logic based MPPT controller are fuzzification, rule-base, inference and defuzzification. There are two inputs to the controller these are error e (k) and change in error Δe (k). The Fuzzification block converts the crisp inputs to fuzzy inputs, while the rules are formed in rule base and are applied in inference block. The defuzzification converts the fuzzy output to the crisp output. The fuzzy inference is carried out by using Mamdani's method, and the defuzzification uses the centre of gravity to compute the output, which is the change in duty cycle. The FLC technique could track MPP under the different atmospheric conditions, but with oscillation about MPP under PSCs. (Islam, *et al*., 2018).

Another online category involves Emerging or nature inspired MPPT techniques, some of them include Particle swarm optimisation (PSO), Firefly optimisation algorithm (FOA), Ant colony optimization (ACO), Cuckoo search (CS), and Radial movement optimization (RMO)

The Particle swarm optimisation (PSO) is a stochastic search method, modelled after the behaviour of bird flocks. The PSO algorithm maintains a swarm of individuals called particles, where each particle represents a candidate solution. The PSO algorithm is applied to realize the MPPT control of a PV system, where in the P-V characteristics exhibits multiple local MPP. However, the PSO experience under PSCs (Koad, *et al.*, 2016).

The Firefly optimisation algorithm (FOA) is Meta heuristic algorithm inspired by flashing of fireflies. One important rule of this algorithm is all fireflies are unisex. It means that regardless of sex, any firefly can be attracted to any other brighter one. Second rule is that flashing light (brightness) is determined from the objective function. Firefly algorithm is superior to other methods in terms of tracking speed, convergence to track global MPP and possesses good tracking efficiency. However, the FA MPPT oscillates (Hemalatha, *et. al.*, 2016).

The Ant colony optimization (ACO) is implemented by making mimicking the ant behaviour .The process starts with randomly initializing the ants. The objective function is framed by including each panel exposure to irradiation and temperature. The Ant MPPT could track MPP under PSCs with oscillation about MPP as the start, but at steady state, the oscillation is absent. Then only simulations results available (Titri, *et al.*, 2017).

The Cuckoo search (CS) technique is an optimisation algorithm inspired by parasitic reproduction of cuckoo birds. The CS MPPT was applied under partial shading conditions and simulation results was reported (Rezk, et al., 2017).

The Radial movement optimization (RMO) technique is a swarm-based stochastic optimization technique. It has several similarities with other techniques such as PSO and DE. The Radial Movement Optimization (RMO) was used under partial shading conditions (PSCs), the result was compared with PSO, and the oscillation about the maximum power point (MPP) was less compared to PSO (Seyedmahmoudian, *et al*., 2016).

3. HYBRID MPPT TECHNIQUES

The third MPPT classification involves hybrid MPPT techniques. Hybrid techniques are the combination of two or more different categories that is used to achieve the desired objective. The MPP is tracked in two steps. The first step places the operating point close to MPP and the second step fine-tunes the operating point close to MPP. Some **e**xamples are the use of fuzzy logic controller (FLC) and genetic algorithms (GA) for optimization (Larbes, *et al.*, 2009). Another one is a Hopfield neural network (HNN) optimized FLC. HNN is utilised to tune automatically the FLC membership functions instead of adopting the trial-and-error approach (Subiyanto and Shareef, 2012).

3 RESULTS AND DISCUSSION

The results of the study and the discussions are presented below.

3.1 RESULTS

The results of the study are presented in Tables 1- 6.

TABLE 1: COMPARISON OF MPPT TECHNIQUES UNDER DIFFERENT ATMOSPHERIC CONDITIONS

Main grouping of MPPT Techniques	Atmospheric conditions			
	Uniform radiation	Rapidly varying radiations	Temperature variations	Partial shading conditions (PSCs)
Offline MPPT Technique				
Fractional Short Circuit Current (FSCC)	✓	–	–	–
Fractional open circuit voltage(FOCV)	✓	–	–	–
Look-up Table Methods	✓	–	–	–
Curve Fitting (CF) Based Methods	✓	–	–	–
Online MPPT Techniques(Conventional)	✓	–	–	–
Perturbation and observation (P&O)	✓	–	–	–
Incremental conductance (Icond)	✓	–	–	–
Online MPPT Techniques((Artificial intelligence)				
Artificial Neural Network (ANN)	✓	✓	✓	✓
Fuzzy Logic Control (FLC)	✓	✓	✓	✓
Differential Evolution (DE)	✓	✓	✓	✓
Genetic Algorithm (GA)	✓	✓	✓	✓
Online MPPT Techniques (Emerging)				
Firefly Optimization Algorithm(FOA)	✓	✓	✓	✓
Ant colony optimization algorithm(ACO)	✓	✓	✓	✓
Particle swarm optimization (PSO)	✓	✓	✓	✓
Cuckoo search (CS)	✓	✓	✓	✓
Radial Movement Optimization (RMO)	✓	✓	✓	✓

TABLE 2: COMPARISON OF MPPT TECHNIQUES VERSUS MPP TRACKING COMPLEXITY UNDER UNIFORM RADIATION

Main grouping of MPPT Techniques	Uniform radiation	Complexity
Offline MPPT Technique		
Fractional Short Circuit Current (FSCC)	✓	Simple
Fractional open circuit voltage(FOCV)	✓	Simple
Look-up Table Methods	✓	Medium
Curve Fitting (CF) Based Methods	✓	Medium
Online MPPT Techniques(Conventional)		
Perturbation and observation (P&O)	✓	Medium
Incremental conductance (Icond)	✓	Medium
Online MPPT Techniques((Artificial intelligence)		
Artificial Neural Network (ANN)	✓	Complex
Fuzzy Logic Control (FLC)	✓	Complex
Differential Evolution (DE)	✓	Complex
Genetic Algorithm (GA)	✓	Complex
Online MPPT Techniques (Emerging)		Complex
Firefly Optimization Algorithm(FOA)	✓	Complex
Ant colony optimization algorithm(ACO)	✓	Complex
Particle swarm optimization (PSO)	✓	Complex
Cuckoo search (CS)	✓	Complex

Radial Movement Optimization (RMO)	✓	Complex

TABLE 3: COMPARISON OF MPPT TECHNIQUES VERSUS MPP TRACKING COMPLEXITY UNDER RAPIDLY VARYING RADIATIONS

Main grouping of MPPT Techniques	**Rapidly varying radiations**	**Complexity**
Offline MPPT Technique		
Fractional Short Circuit Current (FSCC)	–	Simple
Fractional open circuit voltage(FOCV)	–	Simple
Look-up Table Methods	–	Medium
Curve Fitting (CF) Based Methods	–	Medium
Online MPPT Techniques(Conventional)	–	
Perturbation and observation (P&O)	–	Medium
Incremental conductance (Icond)	–	Medium
Online MPPT Techniques((Artificial intelligence)		
Artificial Neural Network (ANN)	✓	Complex
Fuzzy Logic Control (FLC)	✓	Complex
Differential Evolution (DE)	✓	Complex
Genetic Algorithm (GA)	✓	Complex
Online MPPT Techniques (Emerging)		Complex
Firefly Optimization Algorithm(FOA)	✓	Complex
Ant colony optimization algorithm(ACO)	✓	Complex
Particle swarm optimization (PSO)	✓	Complex
Cuckoo search (CS)	✓	Complex
Radial Movement Optimization (RMO)	✓	Complex

TABLE 4: COMPARISON OF MPPT TECHNIQUES VERSUS MPP TRACKING COMPLEXITY UNDER TEMPERATURE VARIATIONS

Main grouping of MPPT Techniques	**Temperature variations**	**Complexity**
Offline MPPT Technique		
Fractional Short Circuit Current (FSCC)	–	Simple
Fractional open circuit voltage(FOCV)	–	Simple
Look-up Table Methods	–	Medium
Curve Fitting (CF) Based Methods	–	Medium
Online MPPT Techniques(Conventional)		
Perturbation and observation (P&O)	–	Medium
Incremental conductance (Icond)	–	Medium
Online MPPT Techniques((Artificial intelligence)		
Artificial Neural Network (ANN)	✓	Complex
Fuzzy Logic Control (FLC)	✓	Complex
Differential Evolution (DE)	✓	Complex
Genetic Algorithm (GA)	✓	Complex
Online MPPT Techniques (Emerging)		Complex
Firefly Optimization Algorithm(FOA)	✓	Complex
Ant colony optimization algorithm(ACO)	✓	Complex
Particle swarm optimization (PSO)	✓	Complex
Cuckoo search (CS)	✓	Complex
Radial Movement Optimization (RMO)	✓	Complex

TABLE 5: COMPARISON OF MPPT TECHNIQUES VERSUS MPP TRACKING MPP COMPLEXITY UNDER PARTIAL SHADING CONDITIONS (PSCS)

Main grouping of MPPT Techniques	**Partial Shading Conditions (PSCS)**	**Complexity**
Offline MPPT Technique		
Fractional Short Circuit Current (FSCC)	–	Simple
Fractional open circuit voltage(FOCV)	–	Simple
Look-up Table Methods	–	Medium
Curve Fitting (CF) Based Methods	–	Medium
Online MPPT Techniques(Conventional)		
Perturbation and observation (P&O)	–	Medium
Incremental conductance (Icond)	–	Medium
Online MPPT Techniques((Artificial intelligence)		
Artificial Neural Network (ANN)	✓	Complex
Fuzzy Logic Control (FLC)	✓	Complex
Differential Evolution (DE)	✓	Complex
Genetic Algorithm (GA)	✓	Complex
Online MPPT Techniques (Emerging)		Complex
Firefly Optimization Algorithm(FOA)	✓	Complex
Ant colony optimization algorithm(ACO)	✓	Complex
Particle swarm optimization (PSO)	✓	Complex
Cuckoo search (CS)	✓	Complex
Radial Movement Optimization (RMO)	✓	Complex

TABLE 6: QUALITATIVE COMPARISON BETWEEN THE METHODS

Type	**Emerging Techniques**	**Artificial intelligence methods**	**Conventional methods**
Tracking Speed	Fast	Medium	Slow
Tracking Accuracy	Accurate	Accurate	Low
Implementation complexity	High	Medium	Low
Dynamic response	Good	Oscillatory	Oscillatory
Periodic tuning	Not Required	Not Required	Not Required

Steady State Oscillations	Low	Medium	High

3.2 DISCUSSIONS

Table 1 show all the MPPT techniques compared under the different atmospheric conditions. The different categories of MPPT techniques are able to track MPP under uniform radiation condition. However, the results differ, because offline techniques give only approximation while conventional techniques are able to track the MPP. Even at that some of the conventional ones like P&O, oscillate about the MPP (Patel, *et al.,* 2013, Kalpana, *et al.,* 2013). It is also clear that the conventional MPPT techniques are not able to track true MPP under rapidly varying radiations, temperature variations and partial shading conditions (PSCs) conditions (Kumar, *et al.,* 2015.). On the other hand, although artificial intelligence MPPT techniques are able to track MPP under the different atmospheric conditions, they have their shortcomings. They are more complex than conventional techniques. For instance, ANN MPPT has to be trained for each PV system. In addition, at PSCs they experience oscillation (Cheema and Kaur, 2014). The implementation complexity of MPPT under uniform radiation is shown in Table 2.

Table 3 shows comparison of MPPT techniques under rapidly varying radiations. As indicated the offline MPPT techniques and conventional MPPT techniques fail to track MPP under rapidly varying conditions. However, online MPPT techniques involving Artificial intelligence and Emerging MPPT techniques were able to track MPP under rapidly varying radiations, even though implementation complexity is high.

Table 4 shows comparison of MPPT techniques under temperature variations condition. Here offline and conventional MPPT techniques fail to track MPP under temperature variations. However, online techniques involving Artificial intelligence and Emerging techniques are able to track MPP under temperature variations, but with more complexity.

Table 5 shows comparison of MPPT techniques under partial shading conditions (PSCs). The table shows that offline MPPT techniques and conventional MPPT techniques fail to track MPP under PSCs. Conversely online techniques involving Artificial intelligence and Emerging techniques are able to track MPP under partial shading conditions even though the implementation complexity is high as compared to conventional or offline MPPT techniques.

Additionally, the Emerging MPPT methods have the advantage that they are fast as indicted in Table 6, but they are complex to implement (Husain, *et al.,* 2016). Besides only simulation results are presently available, practical implementation and evaluation is in progress,

Also, whereas Hybrid techniques could track MPP under the different atmospheric conditions as revealed in Table 1, however, hybrid techniques involving conventional MPPT methods is not able to track MPP under PSCs conditions.

4 CONCLUSION

This paper shows that the different atmospheric conditions have different effect on the maximum power point (MPP), as well as the load. This paper also shows that not all the MPPT techniques are able to track true MPP under different atmospheric conditions. The work shows that many MPPT techniques have been developed to track MPP under uniform radiation, partial shading conditions, but very few under rapidly varying radiations and very scanty development under temperature variations. In addition, the work shows that all the different classification of MPPT techniques is able to MPP under uniform radiation, though with varied results. Additionally, the work shows that offline MPPT techniques and conventional (online} MPPT techniques fail to track MPP under rapidly varying, temperature variations, and partial shading conditions (PSCs). While Artificial Intelligence and Emerging MPPT techniques and some hybrid MPPT techniques are able to track MPP under PSCs. In addition, the study shows that the use of emerging techniques is on the increase, because of its fastness to locate the GMPP, however results available are simulation results.

The paper shows that tracking the MPP under the different atmospheric is vital and is on active research area.

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