International Journals of Power Electronics Controllers and Converters
Vol. 4: Issue 1
www.journalspub.com

Assessment of MPPT-Based Photovoltaic System: A Critical Review

Hira Singh Sachdev[1], *Raghu Chandra Garimella*[2]
Department of Electrical and Electronics Engineering, Madanapalle Institute of Technology and Science, Angollu, Madanapalle, Chittoor District, Andhra Pradesh, India
Department of Electrical and Electronics Engineering, Methodist College of Engineering and Technology, Abids, Telangana, India.

ABSTRACT

In this paper, new approaches are formulated to estimate the parameters and predict the maximum power generated by the PV module at maximum power point under varying environmental conditions. Maximum power point tracking technique is useful for extracting maximum power from PV cell. Here different techniques have been discussed and explained.

Keywords: adder, irradiance, maximum power point (MPP), maximum power point tracking (MPPT), photovoltaic (PV)

Corresponding Author
E-mail: raghuchandhra@gmail.com

INTRODUCTION

Today, renewable energy plays an important role in producing electrical power. The electric power is generated by different modes of generation, such as fossil fuel-fired generation, using diesel oil, petrol, nuclear fuels, hydro–generation, and non-conventional energy sources such as wind power, tidal waves, solar energy, biogas, etc. A PV array under uniform irradiance generates a current–voltage characteristic with a unique point called the maximum power point (MPP); at this point, the array produces maximum output power [1]. A numerical technique is used to extract the maximum power at MPP under varying irradiance and temperature conditions. New expressions are developed to find the PV module's maximum voltage and maximum current at MPP.

MPPT TECHNIQUES

Maximum output power tracking (MPPT) techniques are useful to extract maximum power from the PV system. MPPT controller is used in the PV system. To design a proper MPPT controller, the information about the PV module's maximum power at MPP under varying environmental conditions such as irradiation and temperature is needed. Presently, numerous MPPT techniques are available [1–3]: they are broadly classified into two categories, namely the conventional and soft computing approaches. The open-circuit voltage or short-circuit current, for reference, results in more power loss [4–6]. On the other hand, soft-computing-based MPPT such as artificial neural network (ANN) [7], fuzzy logic [8], differential evolution [9], particle swarm optimization [10, 11], and cuckoo search [12] tend to be more versatile and flexible. Despite exhibiting better steady-state performance, they are much slower and, in practice, are not as acceptable. Maximum power point tracking, frequently referred to as MPPT, operates solar PV modules in a manner that allows the modules to produce all the power they are capable of generating. MPPT is not a mechanical tracking system but it works on a particular tracking algorithm and it is based on a control system. MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different. MPPT algorithms are used to obtain the maximum power from the solar array based on the variation in irradiation and temperature. The voltage at which PV module can produce maximum power is called 'maximum power point' (or peak power voltage). Maximum power varies with solar radiation, ambient temperature, and solar cell temperature. Over the past decades, many methods to find the MPP have been developed. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature changes, hardware needed for the implementation or popularity, among others. Various techniques have been proposed depending on their complexity, sensors used, convergence, setup, and in further aspects [13–23].

Perturb and Observe

The most popular conventional MPPT techniques are the perturb and observe (P&O) [24, 25] and hill climbing [26]. These algorithms are widely used in commercial products, mainly due to their simplicity and robustness.

Only one voltage sensor is used to sense the PV array voltage and the implementation cost is less. The algorithm involves a perturbation on the duty cycle of the power converter and a perturbation in the operating voltage of the DC link between the PV array and the power converter. Perturbing the duty cycle of the power converter implies modifying the voltage of the DC link between the PV array and the power converter. In this technique, the sign of the last perturbation and the sign of the last increment in the power are used to decide the next perturbation. As shown in Figure1, on the left of the MPP, incrementing the voltage increases the power, whereas on the right, decrementing the voltage decreases the power. If there is an increment in the power, the perturbation should be kept in the same direction and if the power decreases, then the next perturbation should be in the opposite direction. Based on these facts, the algorithm is implemented as shown in the flowchart of Figure 2, and the process is repeated until the MPP is reached. The operating point oscillates around the MPP.

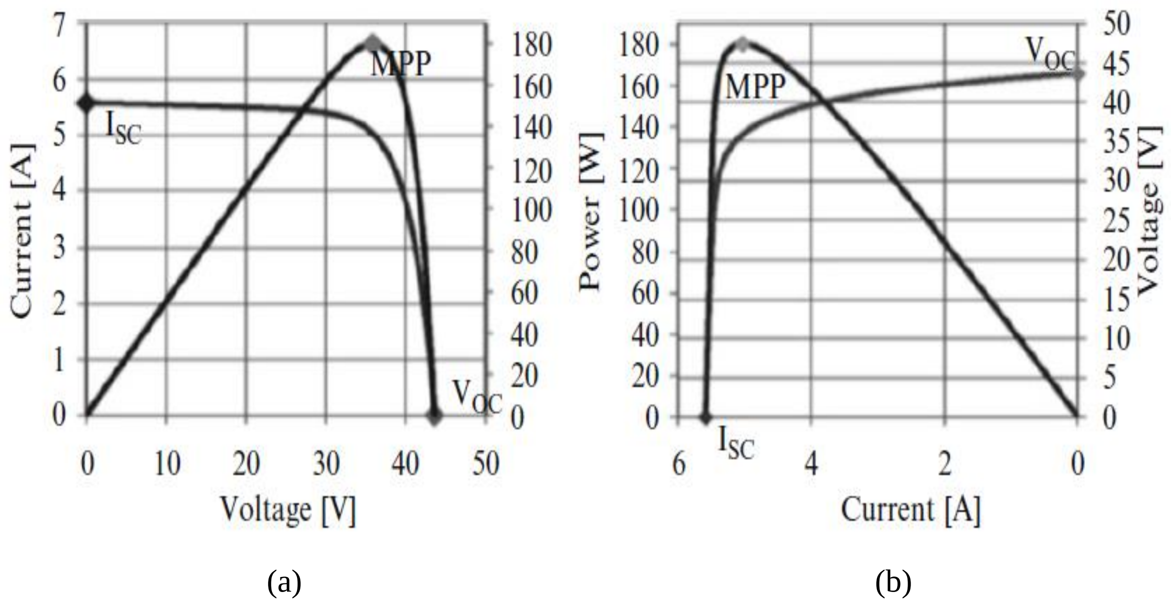


Fig. 1. *PV array characteristic curves.*

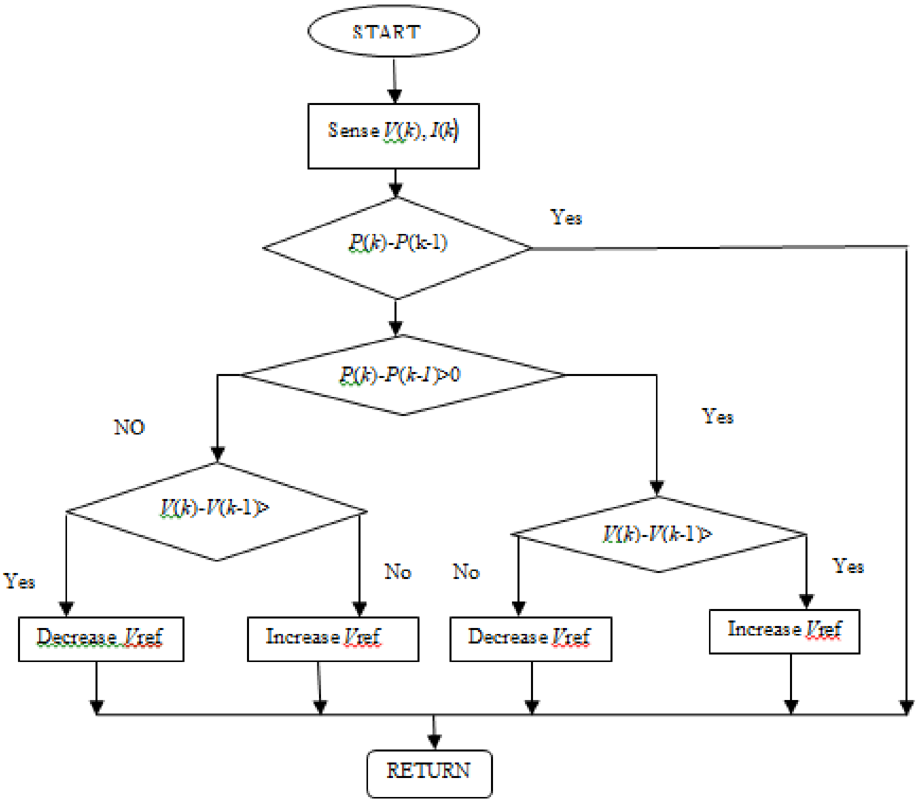


***Fig. 2**. Flowchart of perturb and observe algorithm.*

A drawback of P&O is that, at steady state, the operating point oscillates around the MPP giving rise to the waste of some amount of available energy; moreover, it is well known that the P&O algorithm can be confused during those time intervals characterized by rapidly changing the atmospheric conditions. This drawback is solved by combining a constant voltage (CV) algorithm with a modified P&O. It improves the efficiency under high and low solar irradiation conditions.

P&O with current perturbation and adaptive control algorithm tracks the variable current perturbation, which varies continuously with the irradiance [27].

Incremental Conductance

In the incremental conductance (IC) method [28–32], the slope of the PV power curve is observed to identify the MPP. IC tracking approaches us a fixed iteration step size; it uses the accuracy and tracking speed. The step size may be increased or decreased, so accuracy may also be deceased or increased, respectively. The problem resolves using variable step size [4]. It adjusts the step size to the solar array operating point. The IC algorithm uses two voltage and current sensors to sense the output voltage and current of the PV array. In IC method, the array terminal voltage is always adjusted according to the MPP voltage; it is based on the incremental and instantaneous conductance of the PV module. Figure 3 shows that the slope of the P–V array power curve is zero at the MPP, increasing on the left of the MPP and decreasing on the right-hand side of the MPP. The basic equations of this method are as follows:

$$\frac{dI}{dV} = -\frac{I}{V} \text{ at MPP}$$

$$\frac{dI}{dV} > -\frac{I}{V} \text{ left of MPP}$$

$$\frac{dI}{dV} < -\frac{I}{V} \text{ right of MPP}$$

where *I* and *V* are P–V array output current and voltage, respectively. The left-hand side of equations represent IC of P–V module and the right-hand side represents the instantaneous conductance. When the ratio of change in output conductance is equal to the negative output conductance, the solar array will operate at the MPP. This method exploits the assumption that the ratio of change in output conductance is equal to the negative output instantaneous conductance.

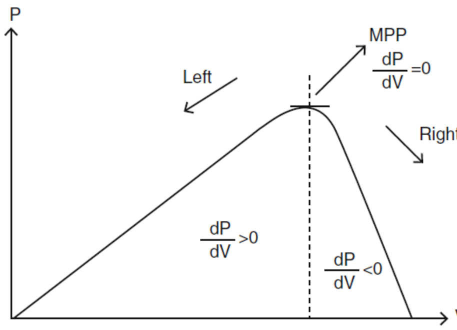


Fig. 3. *Incremental conductance method of solar module.*

Switching ripple detection uses a digital lock-in amplifier to extract the amplitude of the oscillation ripple even in the presence of noise, and it improves the performance both in steady state and transient response [33].

Fractional Open-Circuit Voltage

The near-linear relationship between VMPP and VOC of the PV array, under varying irradiance and temperature levels, has given rise to the fractional VOC method and an effective way to acquire the maximum power [34]:

$$V_{MPP} \cong k_1 V_{oc}$$

where k1 is a constant of proportionality. VMPP is the voltage at MPP and VOC is the open-circuit voltage. Since k1 is dependent on the characteristics of the PV array being used, it usually has to be computed beforehand by empirically determining VMPP and VOC for the specific PV array at different irradiance and temperature levels, fabrication technologies, solar cell technology, fill factor and the meteorological condition. This technique is not useful or supportive in the case of partial shading.

Modified fractional open-circuit voltage method and the current sensor-less method with auto modulation to achieve fast and accurate tracking and improvement demonstrate excellent dynamic response and steady-state performance [35].

Fractional Short-Circuit Current

Fractional ISC results from the fact that, under varying atmospheric conditions, IMPP is approximately linearly related to the ISC of the PV array [36]:

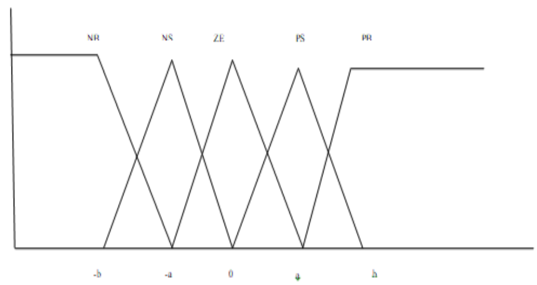
$$I_{MPP} \cong k_2 I_{scc}$$

where k2 is a proportionality constant. Just like in the fractional VOC technique, k2 has to be determined according to the PV array in use. The constant k2 is generally found to be between 0.78 and 0.92. Measuring ISC during operation is problematic. An additional switch usually has to be added to the power converter to periodically short the PV array so that ISC can be measured using a current sensor. This increases the number of components and cost. Power output is not only reduced when finding ISC but also because the MPP is never perfectly matched as suggested by equation. The variable k2 can be compensated such that the MPP is better tracked while atmospheric conditions change. To guarantee proper MPPT in the presence of multiple local maxima, the PV array voltage from open circuit to short circuit periodically sweeps to update k2. Most of the PV systems using fractional ISC in the literature use a

DSP, while a few systems use a simple current feedback control loop instead.

Fuzzy Logic Control

Since last decade, fuzzy logic control (FLC) was popular for MPPT using microcontrollers. Fuzzy logic controllers have the advantages of working with imprecise inputs, not need an accurate mathematical model, and handling nonlinearity. It works on linguistic variables, and is based on natural language and common sense rather than logical thinking. It is not useful for tacking maximum power point, but is helpful for other applications. FLC generally consists of three stages: fuzzification, rule base table lookup, and defuzzification. During fuzzification, numerical input variables are converted into linguistic variables based on a membership function similar to Figure 4. In this case, five fuzzy levels are used: NB (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big).



Numerical variable

Fig. 4. *Membership function for inputs and output of fuzzy logic controller.*

Table 1. *Fuzzy rule base.*

E	Δ*E*				
	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

In some cases, seven fuzzy levels are used probably for more accuracy. Figure 4(a) and (b) is based on the range of values of the numerical variable. The membership function is sometimes made less symmetric to give more importance to specific fuzzy levels. The inputs to an MPPT fuzzy logic controller are usually an error E and a change in error ΔE. The user has the flexibility of choosing how to compute E and ΔE. Since dP/dV vanishes at the MPP, approximation can be applied as follows.

Wu et al. [37] proposed self-tuning fuzzy control for a PV inverter system. The scaling factor of both input and output is automatically tuned to improve the system performance. The hill-climbing search method has been modified, based on FLC for MPPT, under rapidly changing weather conditions [38].

It gives the faster converging speed, less oscillation around the MPP under steady-state conditions, and no divergence from the MPP during varying weather conditions [39]. Adaptive neuro-fuzzy reduces the hardware setup using only one voltage sensor. It increased the array power efficiency and response time, and reduced the hardware complexity [40]. Compared to the performance of fuzzy logic controller with PID controller, it is seen that the performance of fuzzy logic controller is better with respect to stability and speed of response (Table 1).

Neural Network

P&O and IC achieve moderate performance with acceptable implementation complexity. Enhanced performance artificial intelligence-based MPPT techniques have been suggested for better transient and steady-state performance, especially under partial shading and rapidly changing environmental conditions [41–44].
ANN algorithms feature several capabilities such as (i) offline training, (ii) nonlinear mapping, (iii) high-speed response, (iv) robust operation, (v) less

computational effort, and (vi) compact solution for multiple-variable problems [45].

Along with fuzzy logic controllers, another technique of implementing MPPT is the neural networks, which are also well adapted for microcontrollers. Neural networks commonly have three layers: input, hidden, and output layers as shown in Figure 5. The number nodes in each layer vary and are user-dependent. The input variables can be PV array parameters like VOC and ISC, atmospheric data like irradiance and temperature, or any combination of these. The output is usually one or several reference signal(s) like a duty cycle signal used to drive the power converter to operate at or close to the MPP. How close the operating point gets to the MPP depends on the algorithms used by the hidden layer, and how well the neural network has been trained. The links between the nodes are all weighted.

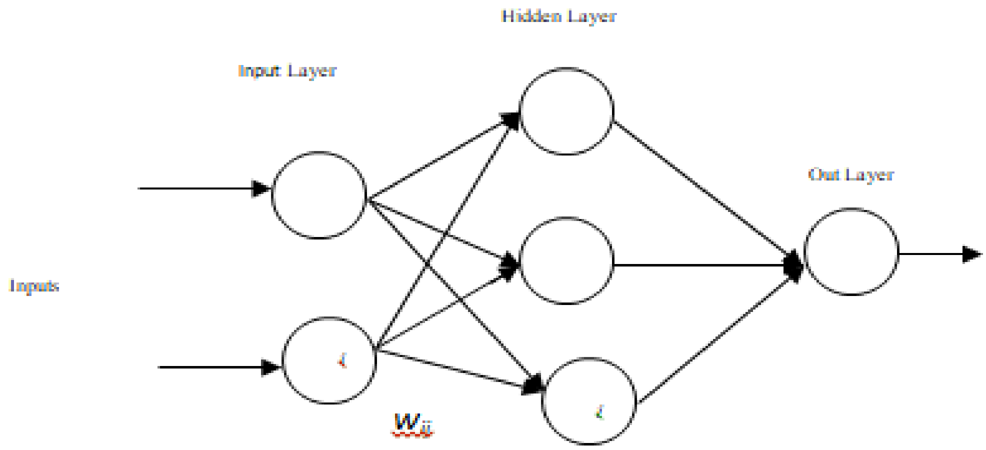


Fig. 5. *Model of neural network.*

The link between nodes i and j is labeled as having a weight of wij in Figure 5. To accurately identify the MPP, the wij's have to be carefully determined through a training process, whereby the PV array is tested over months or years, and the patterns between the input(s) and output(s) of the neural network are recorded. Since most PV arrays have different characteristics, a neural network has to be specifically trained for the PV array with which it will be used. The characteristics of a PV array also change with time, implying that the neural network has to be periodically trained to guarantee accurate MPPT.

A novel ANN-based adaptive predictor–corrector algorithm is used [46], which gives MPP accurately within short time and without any wrong tracking or unwanted power oscillations for all types of insolation changes at different operating temperatures.

Ripple Correlation Control

When a PV array is connected to a power converter, the switching action of the power converter imposes voltage and current ripples on the PV array. As a consequence, the PV array power is also subject to ripple. Ripple correlation control is an optimization technique that takes advantage of the converter signal ripple to track the MPP [47].

Current Sweep

The current sweep method uses a sweep waveform for the PV array current such that the I–V characteristic of the PV array is obtained and updated at fixed time intervals. The VMPP can then be computed from the characteristic curve at the same intervals.

DC-Link Capacitor Droop Control

DC-link capacitor droop control is an MPPT technique that is specifically designed to work with a PV system that is connected in parallel with an AC system line as shown in Figure 6. The duty ratio of an ideal boost converter is given by

$$d = 1 - \frac{V}{V_{\text{link}}}$$

where V is the voltage across the PV array and Vlink is the voltage across the DC link. If Vlink is kept constant, increasing the current going in the inverter increases the power coming out of the boost converter and, consequently, increases the power coming out of the PV array.

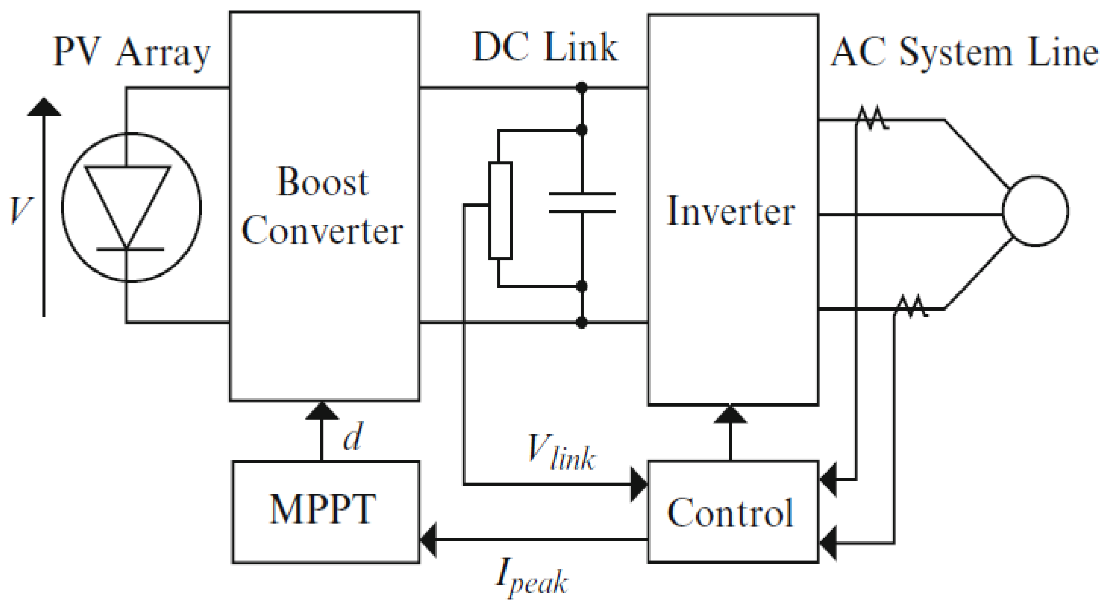


Fig. 6*. Topology for DC-link capacitor droop control.*

Load Current or Load Voltage Maximization

The purpose of MPPT techniques is to maximize the power coming out of a PV array. When the PV array is connected to a power converter, maximizing the PV array power also maximizes the output power at the load of the converter. Conversely, maximizing the output power of the converter should maximize the PV array power, assuming a loss-less converter. Most loads can be of voltage-source type, current-source type, resistive type, or a combination of these. Positive feedback can also be used to control the power converter such that the load current is maximized and the PV array operates close to the MPP. Operation exactly at the MPP is almost never achieved because this MPPT method is based on the assumption that the power converter is loss-less.

dP/dV or *dP/dI* Feedback Control

With DSP and microcontroller being able to handle complex computations, an obvious way of performing MPPT is to compute the slope (dP/dV or dP/dI) of the PV power curve and feed it back to the power converter with some control to drive it to zero. There are several methods to compute the slope. dP/dV can be computed and its sign can be stored for the past few cycles. Based on these signs, the duty ratio of the power converter is either incremented or decremented to reach the voltage source, 4-current-source (Table 2).

Table 2. *Characteristics of MPPT technique.*

MPPT technique	PV array dependent	True MPPT	Analog or digital	Periodic tuning	Convergence speed	Implementation complexity	Sensed parameters
P&O	No	Yes	Both	No	Varies	Low	Voltage, Current
IC	No	Yes	Digital	No	Varies	Medium	Voltage, Current
Fractional V_{oc}	Yes	No	Both	Yes	Medium	Low	Voltage
Fractional I_{sc}	Yes	No	Both	Yes	Medium	Medium	Current
Fuzzy logic control	Yes	Yes	Digital	Yes	Fast	High	Varies
Neural network	Yes	Yes	Digital	Yes	Fast	High	Varies
RCC	No	Yes	Analog	No	Fast	Low	Voltage, Current
Current sweep	Yes	Yes	Digital	Yes	Slow	High	Voltage, Current
DC-link capacitor droop control	No	No	Both	No	Medium	Low	Voltage
Load I or V maximization	No	No	Analog	No	Fast	Low	Voltage, Current
dP/dV or dP/dI feedback control	No	Yes	Digital	No	Fast	Medium	Voltage, Current

CONCLUSION

In this paper, MPP can be improved by several MPPT techniques taken from the literature. Here a common and widely used technique is discussed. MPPT technique is capable of minimizing the ripple around the MPP. A summarized table is presented and its performance can be improved by cooling PV array.

REFERENCES

[1] Esram T, Chapman PL. Comparison of photovoltaic array maximum power point tracking techniques. *IEEE Trans Energy Convers*. 2007; 22(2): 439–449p.

[2] Salam Z, Ahmed J, Merugu BS. The application of soft computing methods for MPPT of PV system: a technological and status review. *Appl Energy*. 2013; 107: 135–148p.

[3] Ahmed J, Salam Z. A critical evaluation on maximum power point tracking methods for partial shading in PV systems. *Renew Sustain Energy Rev*. 2015; 47(7): 933–953p.

[4] Masoum MAS, Dehbonei H, Fuchs EF. Theoretical and experimental analyses of photovoltaic systems with voltage and current-based maximum power-point tracking. *IEEE Trans Energy Convers*. 2002; 17(4): 514–522.

[5] Yuvarajan S, Xu S. Photovoltaic power converter with a simple maximum power point tracker. *Proc Int Symp Circuits Syst*. 2003; 3: III-399–III-402p.

[6] Quoc DP, Nhat QN, Vu NTD, Bao AN, Lee HH, Phuong LM, Khoa LD. The new combined maximum power point tracking algorithm using fractional estimation in photovoltaic systems. In: *Proceedings of IEEE 9th International Conference on Power Electronics and Drive Systems*. 2011, pp. 919–923.

[7] Karatepe SE, Hiyama T. Artificial neural network-polar coordinated fuzzy controller based maximum power point tracking control under partially shaded conditions. IET Renew Power Gen. 2009; 3: 239–253.

[8] Alajmi BN, Ahmed KH, Finney SJ, Williams BW. A maximum power point tracking technique for partially shaded photovoltaic systems in microgrids. *IEEE Trans Ind Electron*. 2013; 60(4): 1596–1606p.

[9] Seyedmahmoudian M, Rahmani R, Mekhilef S, Maung Than Oo A, Stojcevski A, Tey Kok Soon,

Ghandhari AS. Simulation and hardware implementation of new maximum power point tracking technique for partially shaded PV system using hybrid DEPSO method. *IEEE Trans Sustain Energy*. 2015; 6(3): 850–862.

[10] Ishaque K, Salam Z. A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition. *IEEE Trans Ind Electron*. 2013; 60(8): 3195–3206.

[11] Renaudineau H, Donatantonio F, Fontchastagner J, Petrone G, Spagnuolo G, Martin J-P, Pierfederici S. A PSO-based global MPPT technique for distributed PV power generation. *IEEE Trans Ind Electron*. 2015; 62(2): 1047–1058p.

[12] Ahmed J, Salam Z. A maximum power point tracking (MPPT) for PV system using Cuckoo search with partial shading capability. *Appl Energy*. 2014; 119: 118–130.

[13] Esram T, Chapman PL. Comparison of photovoltaic array maximum power point tracking techniques. *IEEE Trans Energy Conv*. 2007; 22(2): 439–449p.

[14] Femia N, Petrone G, Spagnuolo G, Vitelli M. Optimization of perturb and observe maximum power point tracking method. *IEEE Trans Power Electron*. 2005; 20(4): 963–973p.

[15] Femia N, Granozio D, Petrone G, Spagnuolo G, Vitelli M. Predictive & adaptive MPPT perturb and observe method. *IEEE Trans Aerosp Electron Syst*. 2007; 43(3): 934–950p.

[16] Pandey A, Dasgupta N, Mukerjee AK. High-performance algorithms for drift avoidance and fast tracking in solar MPPT system. *IEEE Trans. Energy Conv*. 2008; 23(2): 681–689p.

[17] Sera D, Teodorescu R, Hantschel J, Knoll M. Optimized maximum power point tracker for fast-changing environmental conditions. *IEEE Trans Ind Electron*. 2008; 55(7): 2629–2637p.

[18] Femia N, Petrone G, Spagnuolo G, Vitelli M. A technique for improving P&O MPPT performances of double-stage grid-connected photovoltaic systems. *IEEE Trans Ind Electron*. 2009; 56(11): 4473–4482p.

[19] Brunton SL, Rowley CW, Kulkarni SR, Clarkson C. Maximum power point tracking for photovoltaic optimization using ripple-based extremum seeking control. *IEEE Trans Power Electron*. 2010; 25(10): 2531–2540p.

[20] Ho Lee J, Bae H, Cho BH. Advanced incremental conductance MPPT algorithm with a variable step size. In: *Proceedings of 12th International Conference on Power Electronics and Motion Control (EPE-PEMC'06),* Portoroz, Slovenia. 2006, August 30/September 1, pp. 603–607.

[21] Liu B, Duan S, Liu F, Xu P. Analysis and improvement of maximum power point tracking algorithm based on incremental conductance method for photovoltaic array. In: *Proceedings of 7th International Conference on Power Electronics and Drive Systems (PEDS'07),* Bangkok, Thailand. 2007, November 27–30, pp. 637–641.

[22] Yan Z, Fei L, Jinjun Y, Shanxu D. Study on realizing MPPT by improved incremental conductance method with variable step-size. In: *Proceedings of IEEE 3rd IEEE Conference on Industrial Electronics and Applications*. 2008, pp. 547–550.

[23] Chikh A, Chandra A. An optimum method for maximum power point tracking in photovoltaic systems. In: *Proceedings of IEEE Power and Energy Society and General Meeting,* Detroit, MI, USA. 2011, pp. 1–6.

[24] Sher HA, Murtaza AF, Noman A, Addoweesh KE, Al-Haddad K,

Chiaberge M. A new sensorless hybrid MPPT algorithm based on fractional short-circuit current measurement and P&PO MPPT. *IEEE Trans Sustain Energy*. 2015; 6(4): 1426–1434p.

[25] Elgendy MA, Zahawi B, Atkinson DJ. Assessment of perturb and observe MPPT algorithm implementation techniques for PV pumping applications. *IEEE Trans Sustain Energy*. 2012; 3(1): 21–33p.

[26] Koutroulis E, Kalaitzakis K, Voulgaris NC. Development of a microcontroller-based, photovoltaic maximum power point tracking control system. *IEEE Trans Power Electron*. 2001; 16(1): 46–54p.

[27] Kollimalla SK, Mishra MK. A novel adaptive P&O MPPT algorithm considering sudden changes in the irradiance. *IEEE Trans Energy Conv*. 2014; 29(3).

[28] Hussein KH, Muta I, Hoshino T, Osakada M. Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions. *IEEE Proc Gen Transm Distrib*. 1995; 142(1): 59–64p.

[29] Kuo YC, Liang TJ, Chen JF. Novel maximum-power-point tracking controller for photovoltaic energy conversion system. *IEEE Trans Ind Electron*. 2001; 48(3): 594–601p.

[30] Liu F, Duan S, Liu F, Liu B, Kang Y. A variable step size INC MPPT method for PV systems. *IEEE Trans Ind Electron*. 2008; 55(7): 2622–2628p.

[31] Irisawa K, Saito T, Takano I, Sawada Y. Maximum power point tracking control of photovoltaic generation system under non-uniform insolation by means of monitoring cells. In: *Proceedings of IEEE 28th Photovoltaic Specialist Conference*. 2000, pp. 1707–1710.

[32] Qiang M, Mingwei S, Liying L, Guerrero JM. A novel improved variable step-size incremental-resistance MPPT method for PV systems. *IEEE Trans Ind Electron*. 2011; 58(6): 2427–2434p.

[33] Paz F, Ordonez M. High-performance solar MPPT using switching ripple identification based on a lock-in amplifier. *IEEE Trans Ind Electron*. 2016; 63(6).

[34] Schoeman JJ, Wyk JD. A simplified maximal power controller for terrestrial photovoltaic panel arrays. In: *Proceedings of 13th Annual IEEE Power Electronics Specialists Conference*. 1982, pp. 361–367.

[35] Hua C-C, Fang Y-H, Chen W-T. Hybrid maximum power point tracking method with variable step size for photovoltaic systems. *IET Renew Power Gen*. 2016; 10(2): 127–132p.

[36] Masoum MAS, Dehbonei H, Fuchs EF. Theoretical and experimental analyses of photovoltaic systems with voltage- and current-based maximum power-point tracking. *IEEE Trans Energy Conv*. 2002; 17(4): 514–522p.

[37] Wu TF, Yang CH, Chen YK, Liu ZR. Photovoltaic inverter systems with self-tuning fuzzy control based on an experimental planning method. In: *Proceedings of IEEE 34th IAS Annual Meeting on Industry Applications Conference.* 1999, pp. 1887–1894.

[38] Liu F, Duan S, Liu F, Liu B, Kang Y. A variable step size INC MPPT method for PV systems. *IEEE Trans Ind Electron*. 2008; 55(7).

[39] Alajmi BN, Ahmed KH, Finney SJ, Williams BW. Fuzzy-logic-control approach of a modified hill-climbing method for maximum power point in microgrid standalone photovoltaic system. *IEEE Trans Power Electron*. 2011; 26(4).

[40] Breazeale LC, Ayyanar R. A photovoltaic array transformer-less

inverter with film capacitors and silicon carbide transistors. *IEEE Trans Power Electron.* 2012; 30(03): 1297–1305p.

[41] Bidram A, Davoudi A, Balog R.S. Control and circuit techniques to mitigate partial shading effects in photovoltaic arrays. *IEEE J Photovolt*. 2012; 2(4): 532–546p.

[42] Esram T, Chapman PL. Comparison of photovoltaic array maximum power point tracking techniques. *IEEE Trans Energy Conv*. 2007; 22(2): 439–449p.

[43] Zakzouk NE, Abdelsalam AK, Helal AA, Williams BW. Modified variable-step incremental conductance maximum power point tracking technique for photovoltaic systems. In: *Industrial Electronics Society, IECON 2013 – 39th Annual Conference of the IEEE*. 2013, 10–13 November, pp. 1741–1748.

[44] Abdelsalam AK, Goh S, Abdelkhalik O, Ahmed S, Massoud A. Iterated unscented Kalman filter-based maximum power point tracking for photovoltaic applications. In: *Industrial Electronics Society, IECON 2013 – 39th Annual Conference of the IEEE*. 2013, 10–13 November, pp. 1685–1693.

[45] Elobaid LM, Abdelsalam AK, Zakzouk EE. Artificial neural network-based photovoltaic maximum power point tracking techniques: a survey. *IET Renew Power Gener*. 2015; 9(8): 1043–1063p.

[46] Sekhar PC, Mishra S. Storage free smart energy management for frequency control in a diesel-PV-fuel cell-based hybrid AC microgrid. *IEEE Trans Neural Netw Learn Syst.* 2016; 27(8): 1657–1671p.

[47] Esram T, Kimball JW, Krein PT, Chapman PL, Midya P. Dynamic maximum power point tracking of photovoltaic arrays using ripple correlation control. *IEEE Trans Power Electron*. 2006; 21(5): 1282–1291p.