AIP | Journal of Renewable and Sustainable Energy

Conventional and global maximum power point tracking techniques in photovoltaic applications: A review

A. Pallavee Bhatnagar and B. R. K. Nema

Citation: Journal of Renewable and Sustainable Energy **5**, 032701 (2013); doi: 10.1063/1.4803524
View online: http://dx.doi.org/10.1063/1.4803524
View Table of Contents: http://scitation.aip.org/content/aip/journal/jrse/5/3?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY **5**, 032701 (2013)

Conventional and global maximum power point tracking techniques in photovoltaic applications: A review

A. Pallavee Bhatnagar[a)] and B. R. K. Nema
Department of Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal 462 051 (MP), India

(Received 11 December 2012; accepted 12 April 2013; published online 13 May 2013)

Maximum Power Point Tracking (MPPT) is a technique employed to extract maximum power available from a photovoltaic (PV) module under varying atmospheric conditions. It traces the PV operating voltage corresponding to the maximum power point (MPP) and operates the panel at MPP. However, if a PV array is partially shaded, the conventional MPPT techniques track local MPP and fail to track global MPP. Also, if modules with different optimal currents are connected in series—parallel local MPPs occur in the *P-V* curves and conventional MPPT techniques fail to search global maxima. A lot of literature is available on global MPPT techniques to increase overall system efficiency. The power conditioning unit should, therefore, be capable of searching global maximum power point also. This paper aims at presenting a number of conventional and global MPPT techniques; these methods are discussed in detail on the basis of certain performance parameters.
 [http://dx.doi.org/10.1063/1.4803524]

I. INTRODUCTION

The Photovoltaic (PV) panels are semiconductor devices which convert solar or light energy directly into electricity. With the depletions of conventional energy sources, environmental problems due to conventional energy sources and increase in demand and cost of electric energy, the renewable energy sources especially photovoltaic (solar) energy is gaining greater attention by the researchers. It promises several advantages like pollution free, maintenance free, noise free working conditions. Apart from these advantages, they have certain disadvantages: overall system cost is high and conversion efficiency is also poor. The operational characteristic of PV cell or module is non-linear and depends upon solar insolation and temperature,[1–3] as shown in Figs. 1(a) and 1(b). The PV array has only one point on the *I-V* curve (knee of the curve) where power is maximum, this point is known as Maximum Power point (MPP).[1] With the change in solar insolation and temperature, this MPP moves. To increase the efficiency of PV panel, it is required to operate PV panel at this MPP. Several methods have been reported to operate PV panel at this MPP; these methods are called Maximum Power Point Tracking (MPPT) methods. This function of MPPT is implemented using power electronic interface between PV array and load.

To achieve increased efficiency, various MPPT algorithms have been proposed such as fractional voltage based[4,5] and fractional current based MPPT,[6,7] look up table,[11] curve fitting MPPT,[11] perturb and observation,[12–14] incremental conductance,[17–19] etc. However, these conventional MPPT techniques are suitable under ideal conditions and are not efficient under shading condition. If the PV array is partially shaded due to certain reasons, such as shadow of tree, building, local maximum power points occur on *P-V* curves. Under this condition, the conventional MPPT may track local maximum power point instead of global (actual) MPP, reducing overall system efficiency. Several global MPPT techniques are also reported in different literatures to overcome the problem of partial shading such as analog based MPPT,[8–10] variable step

[a)]Author to whom correspondence should be addressed. Electronic mail: pallaveevbhatnagar@gmail.com

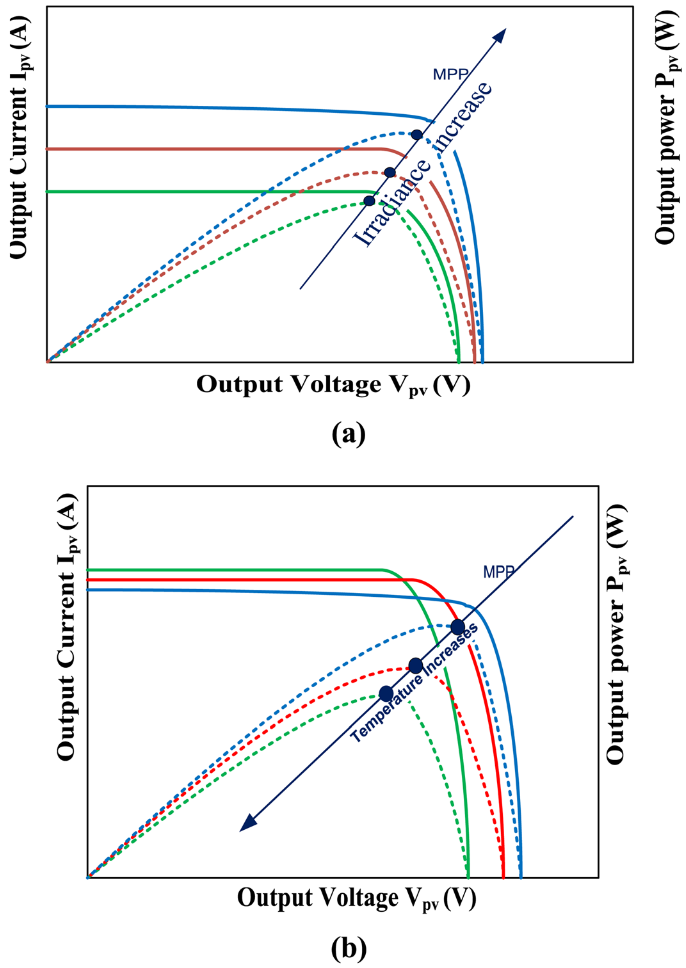

FIG. 1. Characteristic curve of PV panels: (a) different irradiation levels and (b) different ambient temperatures.

incremental conductance (INC),[20] neutral point clamped converter MPPT.[31] Different techniques, as discussed in different literatures, have different advantages and disadvantages with respect to different performance parameters. This paper aims at presenting a comprehensive review of conventional MPPT techniques as well as an attempt is also made to review different global MPPT techniques. The performances of different techniques are compared on the basis of desirable features such as complexity in hardware implementation, sensors required, speed, and range of effectiveness, traceability under partial shading condition, stability and efficiency of the system and economics involved.

The paper is organised in the following three sections: Section II presents an exhaustive review of different conventional and global MPPT techniques along with their advantages and disadvantages. Section III deals with the detailed analysis and comparison of different conventional and global MPPT techniques on the basis of different performance indices. Finally, conclusions are given in Sec. IV.

II. CONVENTIONAL AND GLOBAL MPPT TECHNIQUES

Characteristic curves of PV panels are shown in Fig. 1(a) for different solar irradiances and (b) for different temperatures. The MPP varies with these atmospheric conditions. The solar insolation and temperature conditions are very difficult to predict. The Power Conditioning Units (PCUs), which are usually power electronic converters, are used along with the PV panels. These PCUs perform two functions: first convert DC power from panel to desirable DC/AC

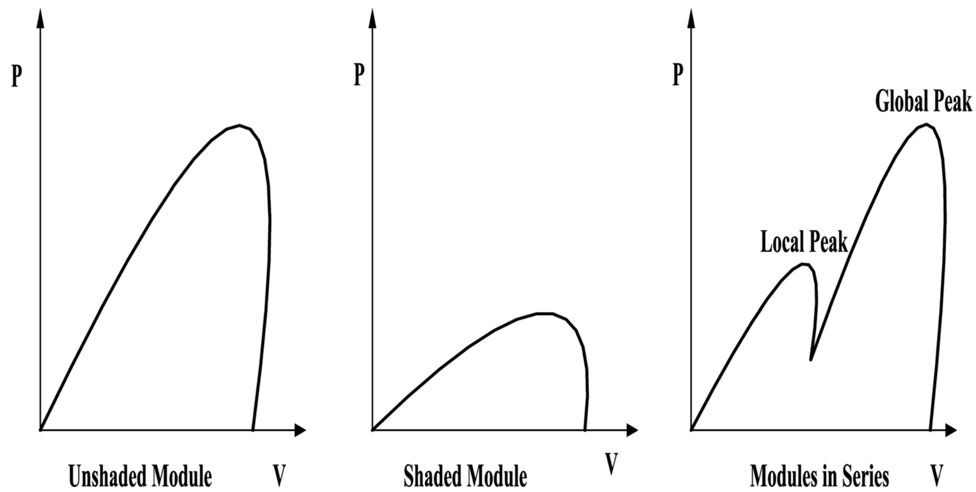

FIG. 2. P-V curve of PV modules connected in series.

power and second extract maximum power from PV panel. A large number of conventional MPPT methods are reported in different literatures to perform this second function.

However, if a PV array is partially shaded by tree, building, or cloud, the conventional MPPT techniques track local MPP and fail to track global MPP. Also, if modules with different optimal currents are connected in series—parallel, local maximum power points occur in the *P-V* curves as shown in Fig. 2, and conventional MPPT techniques fail to search global maxima. A lot of literature is available on global MPPT techniques to search global MPPT and increase overall system efficiency. The PCU should, therefore, be capable of searching global maximum power point also. This paper aims at presenting a number of conventional and global MPPT techniques; these methods are discussed in detail on the basis of certain performance parameters.

A. Fractional voltage (V-MPPT) based MPPT

This is a conventional MPPT technique in which a series switch controlled either by a microcontroller or digital signal processor (DSP) is used to periodically sample the open-circuit voltage V_{OC} of the PV panel.[4] This open circuit voltage exhibits a linear relation with the maximum power point voltage V_M, as given by the following equation (Fig. 3):

$$V_M \cong K_v V_{OC}, \tag{1}$$

K_v is the constant called voltage factor which depends on the *P-V* characteristic of PV panel.[5] For all the sampled values of open circuit voltages, maximum power point voltage is calculated periodically to track MPP.

B. Fractional current (I-MPPT) based MPPT

This conventional method is similar to fractional voltage based MPPT, difference is that instead of series switch a shunt switch is used which samples the short circuit current I_{SC} of the PV panel periodically.[6] This short circuit current exhibits a linear relation with the maximum power point current I_M as given by the following equation (Fig. 4):[6]

$$I_M \cong K_i I_{SC}, \tag{2}$$

where K_i is a constant called current factor.[7] Thus, current at peak power point is calculated periodically using Eq. (2) for samples of short circuit current and MPP is located.

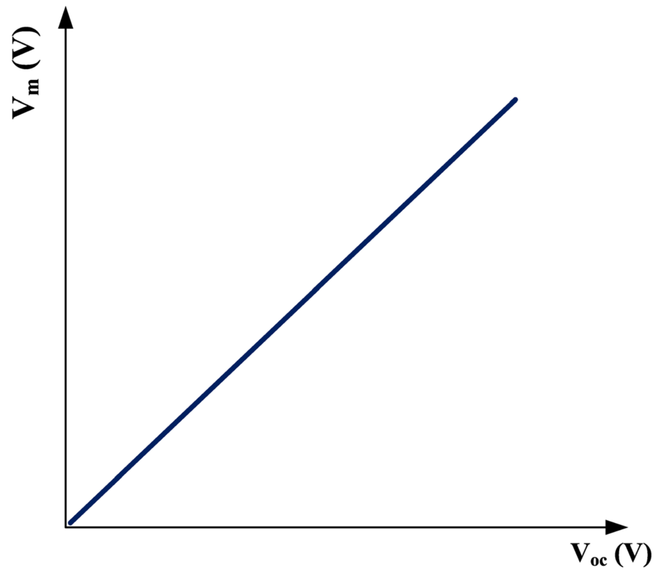

FIG. 3. Linear relation between VOC and VM.

C. Analog MPPT technique

This MPPT technique is applicable for distributed PV applications.[8] It is a global MPPT technique. Distributed PV application allows overcoming several severe problems caused due to mismatch conditions (shadowing effects, variation of temperature, and insolation). In this method, each PV module is connected to individual DC/DC converter; output of each converter is equalised by varying their inputs.[8–10] This MPPT method is advantageous in terms of accuracy and tracking speed also in case of rapidly varying atmospheric conditions. The analog MPPT[8–10] has fast tracking speed and maintains high tracking accuracy. Single-chip circuit implementation reduces power consumption and the high power efficiency of the system is guaranteed. It can track global MPP with same high power efficiency.

D. Look-up table MPPT method

This MPPT technique requires data related to PV panel material, characteristics at different atmospheric conditions.[11] This data stored is compared with the real time data at the time of

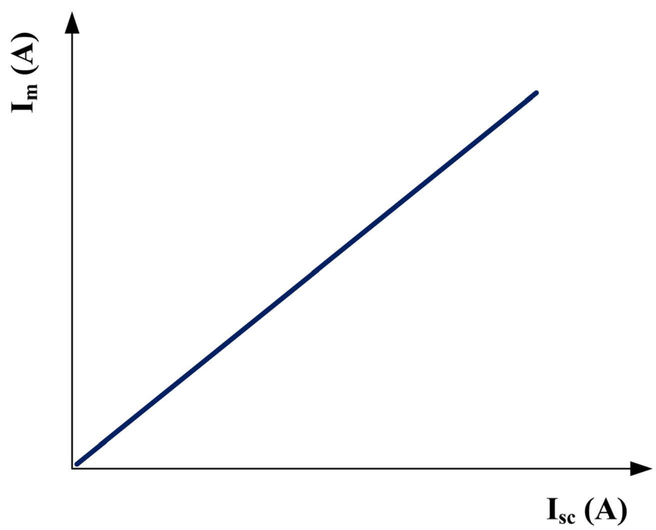

FIG. 4. Linear relation between Isc and Im.

MPP tracking to achieve MPP. This method is very slow; it requires large data storage, and it fails in case of rapidly changing atmospheric condition; also, it cannot track global MPP during partial shading condition.

E. Curve-fitting based MPPT

This technique is a mathematical model based technique, which describes the PV characteristics. Different mathematical equations representing different models of PV panels are used relating voltage and current of PV panel to track MPP. One of such model is as given in Eq. (3), where a, b, c, and d are coefficients, which are calculated periodically with the help of sampled PV voltage V_{PV}, current I_{PV}, and power P_{PV}. Knowing these coefficients, MPP voltage can be calculated using Eq. (4) and MPP can be located,[11]

$$P_{PV} = aV_{PV}{}^3 + bV_{PV}{}^2 + cV_{PV} + d, \quad (3)$$

$$V_M = \frac{-b \pm \sqrt{b^2 - 3ad}}{3a}. \quad (4)$$

Though the method is simple, still it has several disadvantages such as it cannot track MPP under rapidly varying atmospheric conditions and also it cannot search global MPP.[11]

F. The perturb and observe (P&O) MPPT

P&O is the most popular MPPT technique. This is based on tracking MPP by comparing power at different samples and by perturbing voltage or current periodically. The process continues till peak point (MPP) is reached, where change in power with respect to voltage is zero. In this method, PV panel output voltage V_{PV} and output current I_{PV} are sensed. Then power is calculated, *P(k)*, and compared with the power measured in the previous sample *P(k-1),* in order

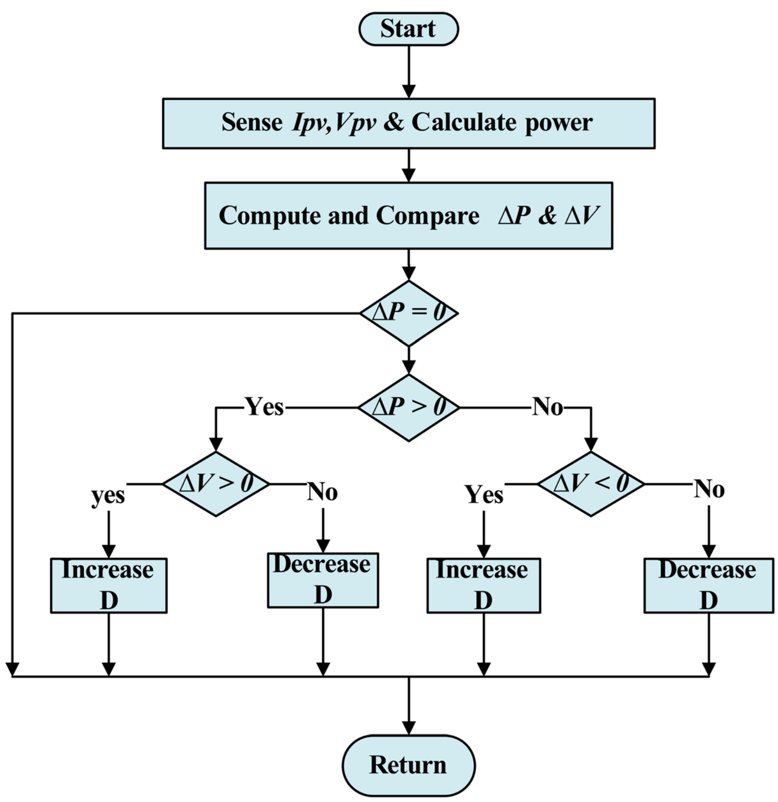

FIG. 5. Flow chart of P&O MPPT.

TABLE I. Conventional P&O method.

S. No.	Change in PV power	Change in PV voltage	Duty cycle
1	+ve	+ve	+ve
2	+ve	−ve	−ve
3	−ve	−ve	+ve
4	−ve	+ve	−ve
5	No change		No change

to get ΔP as shown in Fig. 5. Then according to the sign of ΔP and ΔV, the duty cycle of the converter is changed to reach MPP as given in Table I.[12]

At MPP, the voltage oscillates around the MPP instead of being stably positioned on it, because of continuous voltage perturbation at MPP. This is one of the biggest disadvantages of this method. Also, periodically considerable power loss takes place due to perturbation.[12] So this method does not give good results under rapidly changing atmospheric conditions as shown in *P*-*V* curve in Fig. 6, also speed of this method is slow as it tracks the MPP in several steps.[12]

P&O tracks the MPP by perturbing the PV panel voltage or current in fixed step size. This fixed step size tracking have certain disadvantages like slow speed and large steady state oscillations.[12] If fixed large steps are chosen, it will result in faster dynamics but steady state oscillations also increase and efficiency decreases.[13] However, if small fixed steps are chosen system will slow down.[14]

G. MPPT using advanced technique EPP (estimate perturb-perturb)

As the name suggests, this method uses one estimate for two perturbations as shown in Fig. 7.[15] This method overcomes the problem of rapidly changing environmental conditions and has high speed with high tracking accuracy. This is an advanced P&O method, where drawbacks of P&O method of oscillation around MPP due to continuous perturbations under rapidly changing climatic conditions can be overcome. This increases the speed of tracking without affecting the efficiency. Also, the method can be used to search global MPPT in case of partial shading.[15]

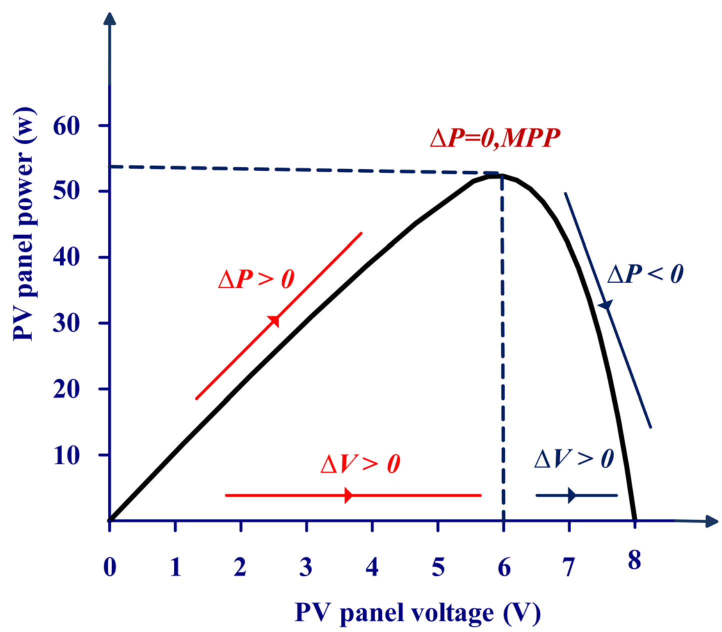

FIG. 6. P-V curve showing P&O MPPT.

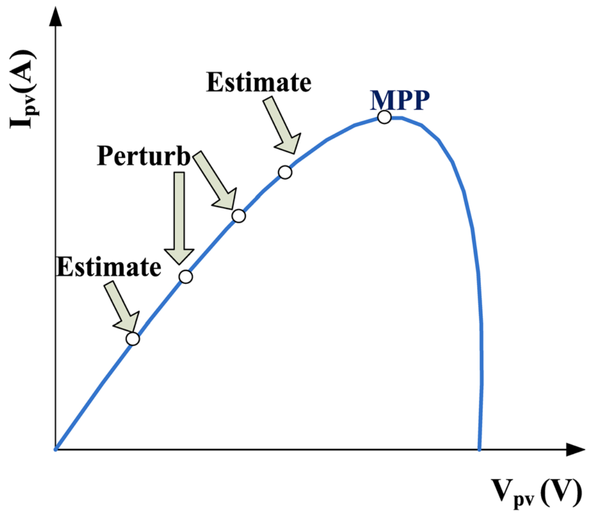

FIG. 7. EPP MPPT.

H. Adaptive P&O MPPT

This is another modified P&O MPPT technique to solve the problem of oscillations around MPP due to rapidly changing atmospheric conditions, which occurs in P&O MPPT. It has advantages of adaptive tracking, no oscillations around MPP during rapidly changing atmospheric conditions, and also it does not require system dependent constants as in Ref. 16. In P&O MPPT if large perturbations are used, it causes oscillations; however, if smaller perturbations are used, it results in slower response where perturbations are system dependent.[16] In adaptive P&O, however, the perturbations are according to system changes, thus improving speed of response and reducing oscillations around MPP. In this method, error between two sampled powers is compared to obtain perturb; at the beginning, perturb steps are larger which increases speed, and then as it approaches MPP, steps are decreased to reduce oscillations.[16]

I. INC MPPT

At MPP change in PV panel output power with output voltage is zero, $dP_{PV}/dV_{PV} = 0$,

$$P_{PV} = V_{PV} I_{PV}. \tag{5}$$

Differentiating P_{PV} with respect to V_{PV} and equating to zero gives

$$dP_{PV}/dV_{PV} = I_{PV} + V_{PV}(dI_{PV}/dV_{PV}) = 0, \tag{6}$$

$$dI_{PV}/dV_{PV} = -I_{PV}/V_{PV}. \tag{7}$$

Equation (7) is the basis of INC MPPT, where I_{PV}/V_{PV} is the conductance and dI_{PV}/dV_{PV} is change in conductance.[17] In this algorithm, the present and previous values of the solar panel voltage and current are sensed and are used to calculate the values of dI_{PV} and dV_{PV} as shown in the flow chart of Fig. 8 on voltage basis. The algorithm is, as shown in Fig. 9, incremental conductance algorithm that exists for current based as well as voltage based control.[18] Thus, in INC MPPT, the instantaneous panel conductance I_{PV}/V_{PV} is compared with the incremental panel conductance (dI_{PV}/dV_{PV}). Voltage at MPP is tracked to satisfy $dP_{PV}/dV_{PV} = 0$, which is MPP as depicted in Table II.[19]

INC based algorithm is advantageous over other conventional methods because it is easy to implement, high tracking speed and better efficiency.[19]

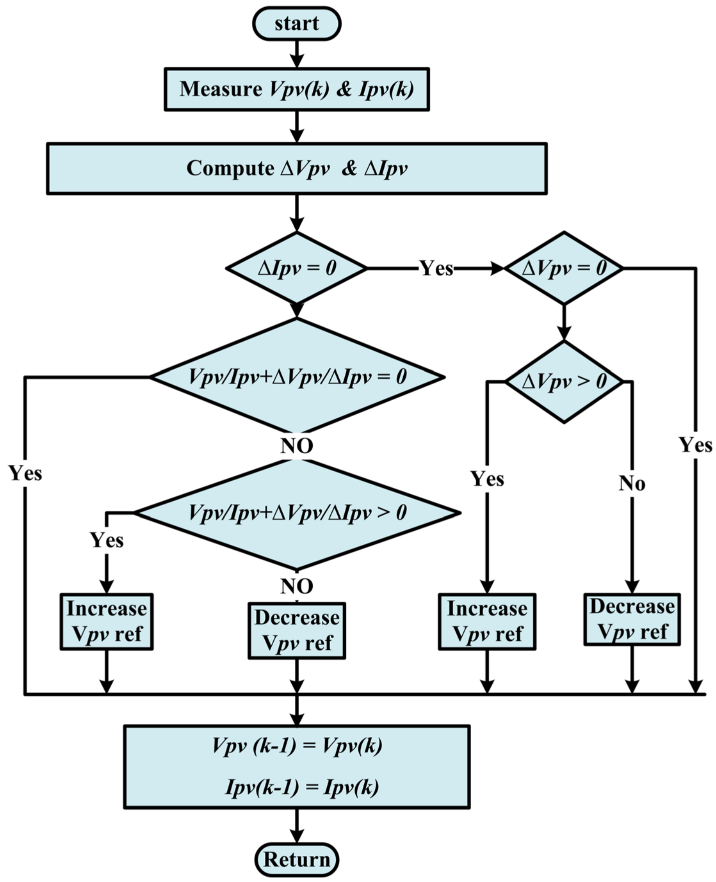

FIG. 8. Flow chart of INC method.

J. Variable step size INC MPPT

The conventional P&O and INC MPPT techniques are very popular techniques of MPPT but these methods suffer from drawbacks of slow speed and oscillations around MPPT. These problems can be overcome if variable steps are used instead of fixed step of tracking.[20] The

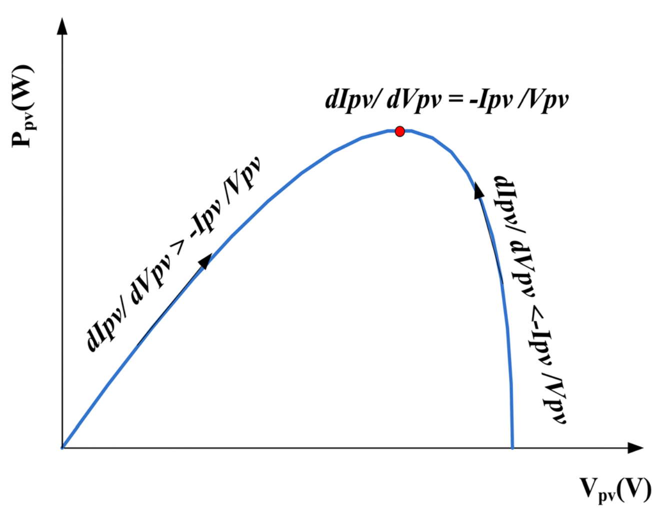

FIG. 9. P-V curve for INC MPPT.

TABLE II. INC method.

S. No.	dP_{PV}/dV_{PV}	dI_{PV}/dV_{PV}	PV curve
1	0	$= -I_{PV}/V_{PV}$	MPP
2	−ve	$<-I_{PV}/V_{PV}$	Right of MPP
3	+ve	$> -I_{PV}/V_{PV}$	Left of MPP

problem of fixed small or large iteration steps can be resolved if MPPT with variable step size is used. The algorithm changes the iteration step size automatically according to the PV array characteristics as suggested in the Variable Step Size INC MPPT algorithm.[20] If the point is far from MPP, the iteration step size increases which enables fast tracking; if the operating point is near to the MPP, the step size becomes very small so that the oscillations are reduced contributing to higher efficiency. This technique gives very good results during rapidly changing atmospheric conditions with minimal oscillations and a good compromise between dynamic and steady state response.[20]

K. Variable step-size incremental-resistance (INR) MPPT

The disadvantages of fixed step size MPPT techniques are oscillations around MPP and slow speed; these can be overcome in variable step size INR method.[21] To overcome this problem, variable steps are used, which are usually large when the system is away from MPP giving faster speed and step size becomes small as system approaches MPP which reduces oscillations around MPP. Usually, variable step size methods are based on the following equation:

$$\delta(k) = \delta(k\text{-}1) \pm K(dP_{PV}/dV_{PV}), \tag{8}$$

where $\delta(k)$ is the duty ratio at sample k and $\delta(k\text{-}1)$ is the duty ratio at sample $k\text{-}1$ and K is the step size factor to control step size.[21] Variable step size INR method is based on the fact that slope of $\frac{dP_{PV}}{dI_{PV}}$ must be zero at MPP as given by the following equation (Table III):

$$\frac{dP_{PV}}{dI_{PV}} = \frac{d(I_{PV}V_{PV})}{dI_{PV}} = V_{PV} + I_{PV}\frac{dV_{PV}}{dI_{PV}} = 0. \tag{9}$$

Thus as in INR method of tracking, the instantaneous resistance $(\frac{V_{PV}}{I_{PV}})$ is compared with incremental resistance $(\frac{dV_{PV}}{dI_{PV}})$ and accordingly MPP is tracked.[21] This method is based on current mode control.

L. MPPT using output parameters

In this method, output parameters like output voltage and current are used for MPPT rather than input parameters.[22] Advantage of this method is that only one output parameter needs to be sensed, reducing cost of system use of output parameters simplifies the MPPT system, irrespective of the nature of load. This MPPT technique is based on the fact that output power

TABLE III. INR method.

S. No.	dP_{PV}/dV_{PV}	$\frac{dP_{PV}}{dI_{PV}}$	PV curve
1	0	$= -\frac{V_{PV}}{I_{PV}}$	MPP
2	−ve	$< -\frac{V_{PV}}{I_{PV}}$	Right of MPP
3	+ve	$> -\frac{V_{PV}}{I_{PV}}$	Left of MPP

increases with output voltage and output current. Thus, maximum power point can be tracked if maximum output voltage or maximum output current, either of them is tracked.[22] At MPP, the output voltage and output current are maximum. Output parameters based MPPT[22] technique has advantages of track ability using single load parameter reducing hardware complexity, and simple controller and less computation as no multiplication and derivations involved and most importantly tracking irrespective of nature of load.

M. Ripple correlation control (RCC) MPPT

Single stage topology (DC-AC) is used in this MPPT. Switching ripples in voltage, current and hence power using filters are used to track MPP instead of using external changes.[23] The time derivative of the time varying power and time derivative of the time varying current or voltage of the panel is controlled to track MPPT.[24] These ripples give information about the change in power and allow us to track MPP since the instantaneous power pulsates at a frequency which is double the frequency of the grid. If power increases, the time derivative of power also increases, and the operating point is below MPP. However, if power is decreasing the time derivative of power is negative than the operating point is above MPP. This method has various advantages like in this method MPP tracking speed can be very high same as power converter switching speed. It is very accurate method, though it is complex to implement.[24]

N. MPPT based on PV module locus characterization

This method uses linear relation that exists between PV module voltage and PV module current at MPP locus.[25] MPP locus is defined as MPP voltage and MPP current expressed as a function of solar irradiation at a given temperature.[25] This MPP locus can be approximated by a line and can be used to track MPP as shown in Fig. 10. MPP locus is not affected by temperature variations. This method is highly effective, less complex, and is suitable for MPP tracking at varying atmospheric conditions. This method can be used effectively with all types of converters.[25] This method, due to the effect of module series resistance, gives better results in case of high solar insolation and high power conditions.[25]

O. Bisection search theorem (BST) based MPPT

The BST is a mathematical method for finding roots.[26] This theorem states that any function $y = f(x)$, which is dependent on x, contains a root x^* between intervals, such that the function $\left(\frac{dy}{dx}\right) = 0$ in that interval. Applying this theorem for PV, $P_{PV} = f(V_{PV})$ is the function and root V_M, lies between interval $[Vsc, V_{OC}]$ where $\left(\frac{dP_{PV}}{dV_{PV}}\right) = 0$, which is MPP as shown in Fig. 11. This point, where the function is zero can be obtained using bisection search theorem which

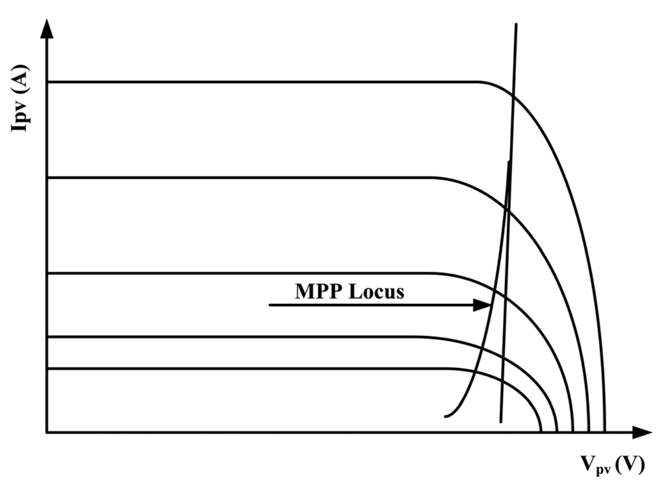

FIG. 10. MPP locus characterization MPPT.

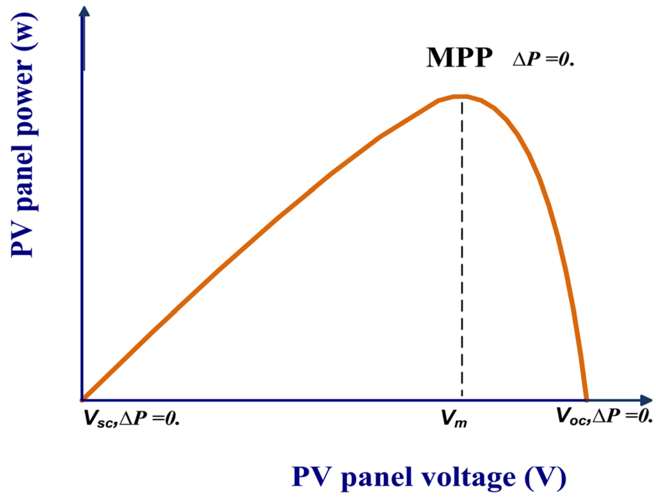

FIG. 11. Bisection search theorem for MPPT.

moves the extreme points closer by having the interval in each step such that the new point is $(\frac{Vsc+V_{OC}}{2})$ and then checks the sign of the function as shown in Fig. 11.[26]

From the *P-V* curve, it can be observed that panel output power is a function of panel output voltage and change in power with respect to voltage, $\Delta P = (\frac{dP_{PV}}{dV_{PV}}) = 0$; at MPP also, it can be observed that when the panel is open circuited $V_{PV} = V_{OC}$, power output and hence change in power ΔP is zero, also when panel is short circuited $V_{PV} = Vsc = 0$, power output and change in power ΔP is again zero and in between these two extreme points there is a voltage $V_{PV} = V_M$ where again $\Delta P = (\frac{dP_{PV}}{dV_{PV}}) = 0$. This voltage is tracked using DC/DC converter and changing its duty cycle. Every time duty-cycle is obtained by halving the sum of previous value and current value which makes system fast and number of sensors required is also one.[26] This technique is simple in hardware requirement, as it requires no derivative calculations, simple and economic in implementation as number of sensors required are less and method is fast as compared to conventional methods.

P. MPPT using golden section search (GSS) algorithm

This is an iterative, non-derivative method of MPPT. This method is based on the fact that maximum value of any function within an interval can be found out using GSS[27] theorem. In case of PV, if V_{oc} and V_{sc} are open circuit and short circuit voltages, and power which is a function of the PV voltage are known at these points and are P_{oc} and P_{sc}. Now (V_{sc}, V_{oc}) is the interval where lies MPP. If power at some other point, Vm1, is known, e.g., Pm1, and is greater than power at P_{sc}, the MPP lies within (V_{sc}, V_{oc}) Fig. 12.[28] If power at some other point, V_{m2}, is known, e.g., P_{m2}, and is greater than power P_{m1}, MPP lies within interval (V_{m1}, V_{oc}) and point V_{sc} is discarded. If, however, P_{m2} is less than P_{m1} as in Fig. 12 MPP lies within interval (V_{m1}, V_{m2}) and point V_{oc} is discarded.[28] This process is repeated between two sections of equal width till MPP is reached. This method is very fast as no derivatives required, robust and is suitable for varying atmospheric conditions.

Q. Slide mode control (SMC) based MPPT method

PV panel characteristics are non-linear. Slide mode control MPPT technique is used for non-linear systems.[29] It uses two stage conversions (DC-DC and DC-AC), where switch of DC-DC converter as in Fig. 13 is controlled according to slide mode control theory to track MPP voltage. If D is the switch function of the converter which controls the output power of the PV panel and $D = 1$ means the switch is close and $D = 0$ means the switch is open. Switch function S is selected as[29]

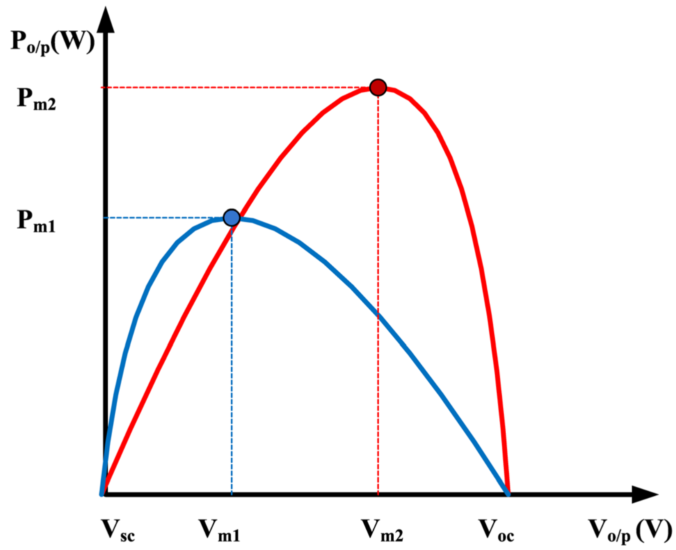

FIG. 12. GSS based MPPT.

$$D = \begin{cases} 0, S \geq 0 \\ 1, S < 0, \end{cases} \tag{10}$$

$$S(x) = \frac{dP_{PV}}{dV_{PV}} = (I_{PV} + \frac{dI_{PV}}{dV_{PV}} V_{PV}). \tag{11}$$

Using Lyapunov function,[30]

$$V = \frac{1}{2} S^2 > 0, \tag{12}$$

$$\dot{V} = S\frac{dS}{dt} = \frac{dP_{PV}}{dDeq} \cdot \frac{d}{dt}\left(\frac{dP_{PV}}{dDeq}\right). \tag{13}$$

Two results are obtained:

(1) When $S > 0$, the system operates on the left of the MPP, $D = 0$, V_{PV} is increasing,

$$\frac{dV_{PV}}{dt} > 0, \tag{14}$$

$$S\frac{dS}{dt} < 0. \tag{15}$$

(2) When $S < 0$ the system is operating in right, $D = 1$, V_{PV} is decreasing,

$$\frac{dV_{PV}}{dt} < 0, \tag{16}$$

$$S\frac{dS}{dt} < 0. \tag{17}$$

The system could reach global stability and the switch function is tending to zero whether the system is operating in the left or right of MPP. The MPPT speed is faster with the increase in switching but power output and voltage output fluctuations increase. The efficiency and accuracy of this MPPT method is high as compared to P&O and INC MPPT.[29,30]

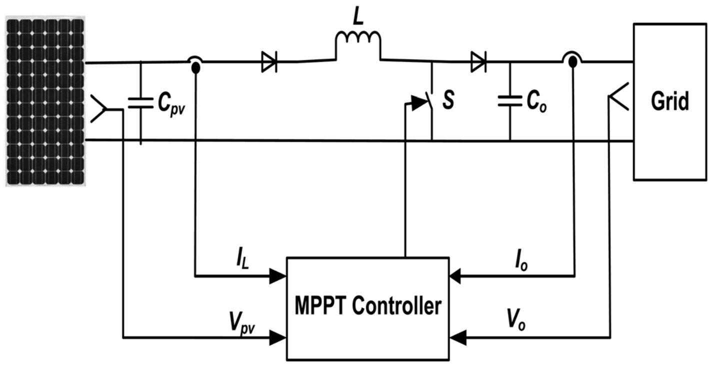

FIG. 13. Slide mode control MPPT.

R. MPPT using neutral point clamped (NPC) converter

This technique is used for tracking MPP of PV module using NPC converters. The NPC converters are essentially required because of ripples present in the neutral of the converter, which is used to determine MPP.[31] This is based on the fact that power for maximum and minimum ripples can be determined if the ripple is known. The panels are connected in series and NPC converter's neutral point is connected in a way of dividing the array into two half.[31] Now the voltages of both the panels are adjusted to get MPP. The frequency of neutral point voltage is three times the frequency of the grid, so it is possible to find out the maximum and minimum value of voltages.

S. Temperature based MPPT

This method is based on the fact that the open-circuit voltage of the solar cell varies with the cell temperature whereas the short-circuit current is directly proportional to the irradiance. This MPPT method is simple in implementation; cost wise is also cheaper and above all has a good tracking factor.[32] It uses temperature sensors for tracking MPP as MPP varies with temperature and MPPT algorithm along with temperature function is used to track MPP.[32] But this method suffers from certain disadvantages also, such as PV array temperature is not uniform throughout and temperature sensor is a problem for measurement which may cause wrong and slow tracking.[32]

T. MPPT based on model reference adaptive

This MPPT technique is based on Lyapunov model of reference adaptive control.[33] In this model when the characteristics of PV panel changes with the change in environmental conditions the adjustable parameters are adjusted by adaptive mechanism to overcome the effect of parameter changes.[33] In adaptive algorithm, the accuracy, feasibility, and robustness are high and Ref. 33 shows that the adaptive algorithm could greatly improve the utilization ratio of solar arrays

U. MPPT using direct search algorithm

This is a novel MPPT technique which uses the dividing rectangles (DIRECT) theorem.[34] Power-voltage equation of PV cells is considered as Lipschitz function and global maxima is this function is searched,[35]

$$|P(V1) - P(V2)| \leq M|V1 - V2| \forall V1, V2 \in [a, b]. \tag{18}$$

Equation (18) is the Lipschitz function[35] pplied to PV module with constant M, V is a variable bounded in interval [a, b]. For different samples with different values of M (large initially and smaller later), global peak can be searched periodically. Initially, a sample of voltage is taken at the center of an interval with large step, and then two samples are taken at the center points of left and right intervals. This process is repeated till global peak reached satisfying Lipschitz function.[36] The advantage of this method is its capability of searching global maxima with fast tracking speed and robustness. The DIRECT algorithm has relatively very good performance and fast speed even in case of multiple MPP and sudden high level changing of insolation.[36]

V. Transient based MPPT

This technique uses single stage conversion, where PV voltage or current is controlled by inverter. It is based on the MPP detection during transient process, introduced according to the irradiance change.[37] Whenever there is a change in irradiance current changes and so changes the power, only current is required to be sensed. *P*-*V* curves for three different insolations and flowchart are shown in Fig. 14.

As the insolation decreases, the power output also decreases to new operating point which is not MPP so as reference voltage, and operating point shifts toward left to new MPP. New power is sampled and compared, once the maximum power is sensed that the reference value of the voltage is set.

In this method transient is sensed, reference voltage is changed accordingly, and MPP is tracked. This method tracks MPP and locks it by setting voltage reference hence oscillations in steady state is avoided, MPP during rapidly changing atmospheric conditions can be quickly and accurately computed. System requirement is simple in this method as only current is sensed.[37] Another advantage is that the transient process need not be triggered frequently when irradiation changes slowly.

W. MPPT using extremum seeking (ES)

This MPPT technique is faster, robust, and requires less sensors and more stable as compared to conventional MPPT methods like P&O and INC. This method is different from conventional methods as it uses the ripples in the inverter.[38–40] Hardware used is shown in Fig. 15,

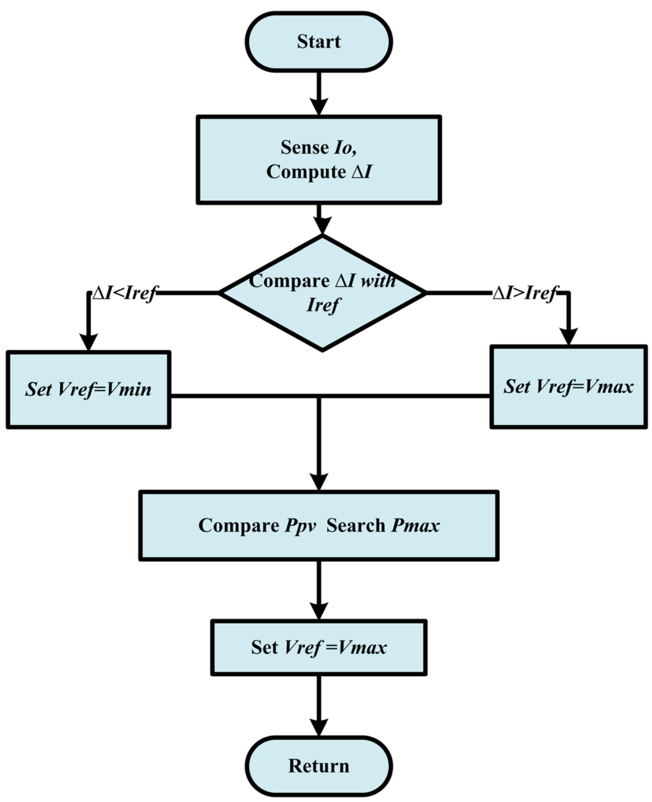

FIG. 14. Transient MPPT flow chart.

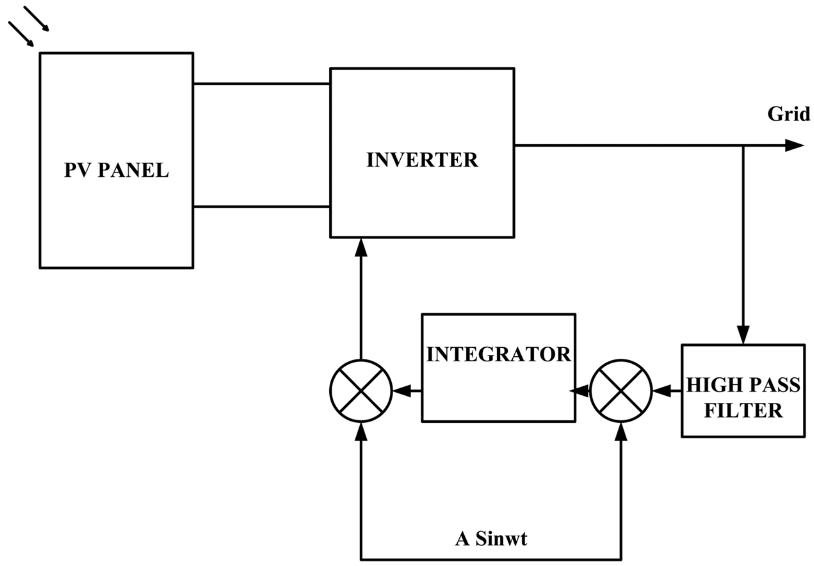

FIG. 15. ES MPPT.

$$LC\frac{d^2Ipv}{dt^2} + C\frac{\partial f}{\partial Ipv}\frac{\partial Ipv}{\partial t} + Ipv = u - C\frac{\partial f}{\partial G}\frac{dG}{dt}. \tag{19}$$

Equation (19) is the basis of extremum seeking MPPT where u is the inverter control current, *Ipv* is the array current, LC is the low pass filter between u and i.[38] The extremum seeking MPPT,[38,39] compared with other conventional methods gives better results in total power efficiency, and in transient rise-time to the maximum power point. Also, it guaranteed convergence and stability properties which are ideal for variable weather conditions and system dynamics.

X. Numerical calculations based MPPT

The problem of low convergence speed and low accuracy can be solved using algorithm based on numerical calculations.[41,42] This algorithm uses the parabolic model for PV with voltage and current as parameters and using quadratic interpolation method, the voltage at MPP is calculated at a particular atmospheric condition.[41] Let V_O, V_1, and V_2 represent the three voltage values at three operating points on the *P-V* curve, P_O, P_1, and P_2 represent the power values corresponding to the voltage values as in Fig. 16,

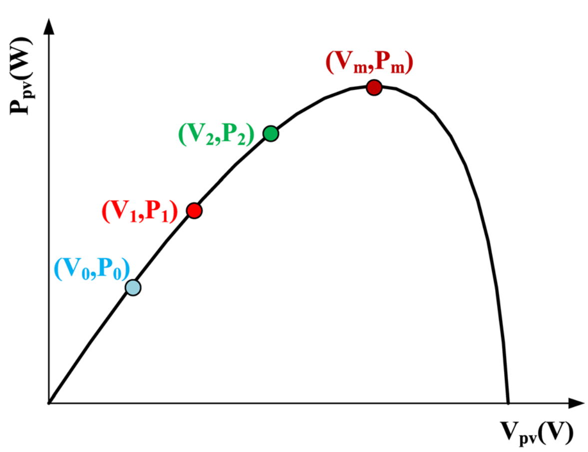

FIG. 16. MPPT based on numerical calculations.

$$Q(V) = Q_O(V)P_O + Q_1(V)P_1 + Q_2(V)P_2, \tag{20}$$

where $Q(V)$ is the quadratic interpolation polynomial, $Q_O(V)$, $Q_1(V)$, $Q_2(V)$, are quadratic interpolation basis functions and are given by following equations:

$$Q_O(V) = (V - V_1)\,(V - V_2)/(V_O - V_1)(V_O - V_2), \tag{21}$$

$$Q_1(V) = (V - V_O)(V - V_2)/(V_1 - V_O)(V_1 - V_2), \tag{22}$$

$$Q_2(V) = (V - V_O)(V - V_1)/(V_2 - V_O)(V_2 - V_1), \tag{23}$$

and the quadratic interpolation function is expressed as the following equation:[41]

$$\begin{aligned} Q(V) = {} & (V - V_1)\,(V - V_2)/(V_O - V_1)\,(V_O - V_2)P_O \\ & + (V - V_O)(V - V_2)/(V_1 - V_O)\,(V_1 - V_2)P_1 \\ & + (V - V_O)(V - V_1)/(V_2 - V_O)(V_2 - V_1)P_2. \end{aligned} \tag{24}$$

At MPP, ($dQ(V)/dV = 0$) is zero.

$$dQ(V)/dV = 2(r_1 + r_2 + r_3)V - [r_1(V_1 + V_2) + r_2(V_O + V_2) + r_3(V_O + V_1)] = 0. \tag{25}$$

Calculating the values of r_1, r_2, and r_3, voltage at maximum power point is obtained as

$$V_M = r_1(V_1 + V_2) + r_2(V_O + V_2) + r_3(V_O + V_1)/2(r_1 + r_2 + r_3). \tag{26}$$

This algorithm can calculate the exact voltage value of MPP as it is based on numerical calculations so it can track the MPP in one step.[42]

Y. MPPT using one cycle sampling technique

Most of the conventional MPPT techniques use two stages one for MPPT and other for DC to AC conversion. One cycle sampling MPPT technique uses single stage conversion (full bridge DC to AC) including buck-boost conversion for MPPT. This single stage injects the sinusoidal current in the grid and also performs MPPT. MPPT is achieved with the buck boost control of capacitor voltage at the input side of the converter.[43,44] Whenever there is a difference in power delivered to the grid and power at the input of buck boost converter, voltage at the input of buck-boost converter side capacitor is changed. Hardware used is as shown in Fig. 17, while the voltage across the capacitor on the output side of the buck boost converter is used to define the reference amplitude of the current injected in the grid.[43,44] One Cycle Sampling technique allows the implementation of a discrete and low cost MPPT controller at low cost and analogue multiplier, instead of the costly DSP.

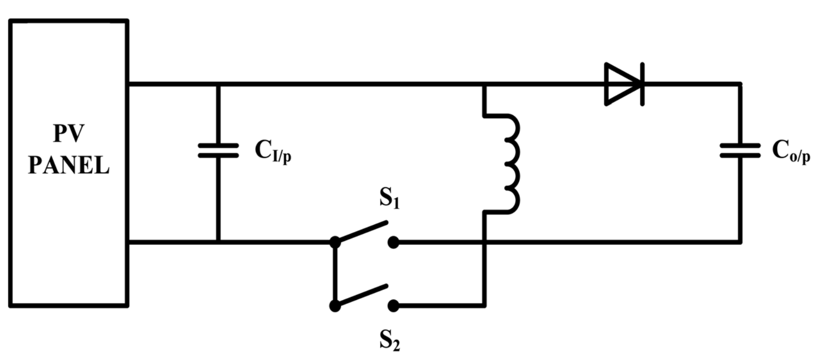

FIG. 17. One cycle control based MPPT.

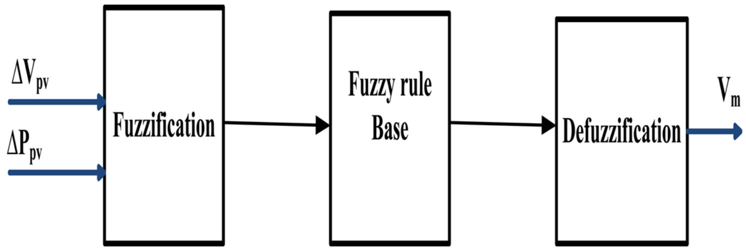

FIG. 18. FLC based MPPT.

Z. Fuzzy logic control (FLC) based MPPT

In this MPPT, output voltage of the converter is changed according to the error input (voltage error, V_e) and change in error input (ΔV_e) such that panel output voltage becomes equal to the voltage corresponding to MPP.[45] The voltage error is obtained by comparing the array voltage V_{pv} with the reference voltage V_{ref}; the reference voltage corresponds to the maximum array voltage V_m at a particular solar insolation at that instant. This maximum voltage changes according to solar insolation. FLC works in three steps: fuzzification is a process in which the numerical values (voltage error: V_e and change in error: ΔV_e) are converted into linguistic variable. Then the membership functions for the inputs are chosen in a range of $[-1\ 1]$.[45] In MPPT, voltage and power are the two variables which are used in describing the control rules which are to be expressed in terms of fuzzy set with linguistic variables as shown in Fig. 18. Then the input variables namely change in voltage and change in power

The rule base corresponding to fuzzy inputs and outputs are derived from the system behaviour in the form of IF-THEN rules. Rule base tables are obtained which gives several possible combinations of the degree of supports with varying strengths to the corresponding rules, to satisfy different conditions.

In this process, the linguistic variables are converted back to numerical variables as the output of fuzzy controller based on the membership function.

The terminal voltage and reference voltages are sampled periodically and voltage error $V_e = V_{ref} - V_{PV}$, and change in error are computed, then the fuzzy controller determines the control action and computes the desired change in the control voltage for the pulse width modulation (PWM) generator which further changes the duty ratio of the converter to bring the operating point to MPP.

AA. Particle swarm optimisation (PSO) based MPPT

PSO is an intelligence based algorithm; it has many advantages when applied to PV applications for MPP tracking like it requires very few parameters for MPP search, it can search global MPP and is very simple.[46,47] In PSO, the position and speed of all the particles are initialized in a random way in solution space, where particles position denotes the result of objective function and speed denotes the direction and speed of particle. The information is transferred from optimised particle to other particles in the solution space this iteration continuous to achieve the goal.[46]

In PV application, it is mostly applied where exhibits multiple local MPP. When the terminal voltages for two PV modules one shaded other un-shaded are different giving total output power which is not maximum power. PSO can be applied to obtain global MPP by considering individual voltages and controlling them individually as N dimensional row vector.[46] The PSO method[46,47] is a simple and effective method that can be applied to a multivariable function optimization having many local optimal points, with less cost. This approach can search global MPP even under complex partial shading conditions.

AB. Complex particle swarm optimization (CPSO) MPPT

CPSO MPPT solves the problem associated with PSO (particle swarm optimization) of premature convergence problem by quickly searching local optimal point.[48] The two major disadvantages of PSO MPPT as given by Ref. 48 are: first, in case of complex problems it is incapable of searching maxima; second, local convergence accuracy is not high. These two problems can be overcome using CPSO MPPT. This method does not require gradient of the objective function so it is simple and cheaper. It requires reflection, contraction, and expansion to obtain MPPT.[48] First, all vertices are find out for maxima, then vertex with good performances are used for next search this process is repeated till MPPT reached.

AC. Artificial neural network (ANN) based MPPT

The ANNs are new emerging technology used to solve complex problems. ANN are used for the on-line estimation of the insolation–dependent reference voltage, since MPP voltages nonlinearly related to the solar insolation linear function approximation techniques are not suitable.[49] ANN uses feed-forward neural network. Input of ANN consists of solar irradiance and cell temperature. The information moves from input, hidden, and to output layer only in one direction. The offline ANN can be used to estimate this maximum voltage at a particular insolation. The ANN has an advantage that they do not require detailed information of the system. PSO is another intelligent control technique used nowadays in maximum power point tracking.[49] This method is mostly used where multiple maxima are found in *P-V* curve it works efficiently under partial shading condition.

AD. MPPT using OIF-Elman network

This MPPT method is based on OIF (Output-Input Feedback)—Elman neural network.[50] This method has an advantage of tracking MPP at a very fast speed, during rapidly changing atmospheric condition along with its simplicity. This method uses Cuk-converter, duty cycle of which is changed to obtain MPPT.[50] It uses feedback from hidden nodes as well as from output nodes.

AE. MPPT based on dual-carrier chaotic search

This MPPT is based on chaos search theorem on dual carrier.[51–53] The advantage of this method is its high efficiency and that it can solve the problem of multiple MPP with faster convergence speed and accuracy. The chaos according to Ref. 51 means randomness, chaos variables are used to search MPPT because of its regularity and sensitivity. It uses iteration formula to obtain MPPT producing Chaos variables in continuous variable space. The dual carrier approach improves the accuracy, efficiency, and precision.

It is based on Eq. (27),[51]

$$max f(x_i), i = 1, 2, 3, \ldots\ldots\ldots, n\, xi \in [a_i, b_i], \tag{27}$$

where x is the optimization variable *f(x)* is the objective function in case of PV it is panel output power.

AF. Switched capacitor (SC) based MPPT

This is a novel MPP tracking method very efficient specially under partially shading condition.[54] It matches the input resistance of the SC dc-dc converter to the output resistance of the array to achieve MPPT. SC converter consists of capacitors to buck or boost power from PV source to load without use of inductors and transformers.[54–56] Thus, from the P-V curve the resistance of the PV array is calculated which is then matched with the input resistance of the SC converter by controlling the frequency of switching and PWM.

AG. MPPT based on hysteresis comparison and optimal gradient

In this method, first the power P_n at a particular sample is determined then based on optimal gradient method perturbation steps are determined.[57] Next the voltage, current, and hence power (P_{n+1} and P_{n-1}) on both sides of the point, where sample taken is determined. Now the DC side capacitor disturbance voltage reference is set as[57]

If $Pn + 1 \geq Pn > Pn - 1$,

the reference for the next cycle is set as V_{k-1}.

If $Pn + 1 \leq Pn > Pn - 1$,

the reference for the next cycle is set as V_{k+1}.

For all other conditions, the reference is set as $V_{k.}$ This way MPP can be tracked quickly and with reduced oscillations around MPP.[57]

AH. Linear–prediction based MPPT

This MPPT method is better than other conventional MPPT methods with respect to response speed, accuracy, and steady state and dynamic response. This works in two parts: first, searches the MPP by using linear prediction with improved speed; second, error correction with improved accuracy.[58] The method is based on principle that the non-linear *I-V* curve of PV panel consists of a constant current region and a constant voltage region, assuming any one parameter either voltage or current constant the PV power will depend on the other parameter, thus linear prediction is applied to determine MPP.

III. MPPT TECHNIQUES: EVALUATION AND COMPARISON

Around 34 different MPPT techniques are discussed in this paper. These techniques vary in control strategies, variables, hardware implementation, and circuitry used by them. Each method has its own advantages and disadvantages with respect to these parameters. Fractional voltage and fractional current based method discussed in Sec. II are conventional, old but very popular MPPT techniques. Tracking speed of both techniques are high, as no derivatives are to be computed, sensors required are less and are practical method for MPP estimation.[4,5] But both the techniques suffer from loss of power during sampling of short circuit current and open circuit voltage. I-MPPT requires hardware which is more complicated and expensive as shunt switch is required and has more losses as compared to hardware V-MPPT of same rating. Accuracy of I-MPPT is more compared to V-MPPT, whereas voltage based technique is more efficient and has fewer losses.[6,7] The advantage of V-MPPT is that it is simple and economic and uses only one feedback loop, but disadvantage is that it is not effective in varying temperature and insolation conditions. Also, this method cannot be applied in the battery energy storage system.

The P&O and INC methods are most popular conventional MPPT methods. But P&O technique faces severe problem of oscillation around MPP, due to which there is considerable loss of power.[12] Also, the response of P&O algorithm is slow under fast changing environmental condition as pointed out in Ref. 13. adaptive P&O,[16] variable step INC,[20] EPP,[15] and variable step size incremental resistance method INR[21] are few methods discussed to overcome disadvantages of P&O and INC MPPT.

The analog MPPT[8–10] has fast tracking speed and maintains high tracking accuracy. Single-chip circuit implementation reduces power consumption and the high power efficiency of the system is guaranteed. It can track global MPP with same high power efficiency.

RCC method has certain advantages over P&O methods and is discussed in Refs. 23 and 24. Slide mode control technique is proposed in Refs. 29 and 30. Temperature method of MPPT is also presented in Ref. 32. This method has certain advantages, it is very simple in implementation and cost is also less.

Locus characterisation MPPT[25] is highly effective, less complex, and is suitable for MPP tracking at varying atmospheric conditions. This method can be used effectively with all types of converters.[25] This method, due to the effect of module series resistance, gives better results in case of high solar insolation and high power conditions.[25]

Apart from this, there is another method called Bisection Search Theorem based MPPT is reported in Ref. 26, which is mostly used when PV array exhibits two or more MPPs under varying climatic conditions where use of other techniques is a difficult task. However, the BST is simple in hardware requirement as it requires no derivative calculations, economic in implementation as number of sensors required is less and fast in MPP tracking. GSS MPPT[27,28] is a novel technique has advantages of fast response, robust (it does not require derivatives), and guaranteed convergence.

The DIRECT algorithm[36] has relatively very good performance and fast speed even in case of multiple MPP and sudden high level changing of insolation. The advantage of this method is its capability of searching global maxima with fast tracking speed and robustness.

The transient based method[37] is different from other conventional methods as it does not contain energy buffer stage DC/DC, also it is based on the MPP detection during transient process introduced according to the irradiance change but is not based on continuous perturbation.

The extremum seeking MPPT,[38,39] compared with other conventional methods, gives better results in total power efficiency, and in transient rise-time to the maximum power point. Also, it guaranteed convergence and stability properties which are ideal for variable weather conditions and system dynamics.

The conventional MPPT algorithms like P&O and INC cannot track MPP in one step as these are iterative approach which senses, calculates, and perturbs periodically so the tracking is slow and not stable at MPP. The problem of speed, stability, and accuracy can be solved using this MPPT algorithm based on numerical calculations.[41,42]

One cycle sampling technique allows the implementation of a discrete and low cost MPPT controller at low cost and analogue multiplier, instead of the costly DSP. In adaptive algorithm, the accuracy, feasibility, and robustness are high and Ref. 33 shows that the adaptive algorithm could greatly improve the utilization ratio of solar arrays

FLC[45] and ANN[49] are intelligent methods of MPPT tracking, these methods have the advantage of working with imprecise inputs, not needing an accurate mathematical model and handling nonlinearity and they are more robust than conventional nonlinear controllers. The PSO method[46,47] is a simple and effective method that can be applied to a multivariable function optimization having many local optimal points, with less cost. This approach can search global MPP even under complex partial shading conditions.

Output parameters based MPPT[22] technique has advantages of track ability using single load parameter reducing hardware complexity, and simple controller and less computation as no multiplication and derivations involved and most importantly tracking irrespective of nature of load.

IV. CONCLUSION

Around 34 different MPPT techniques for photovoltaic applications are discussed in Sec. II of this paper along with their advantages and disadvantages. Selection of a particular MPPT technique for a particular application forms such large number of existing techniques is a difficult and confusing task, since each technique has certain advantages and disadvantages. To overcome this problem, many literatures are available which present comparative study of different MPPT algorithms.

This paper also aims at discussing problem MPPT under partial shading condition which reduces system efficiency even with MPPT controllers. A comprehensive review of different global MPPT techniques is also made in this paper. This review paper discusses MPPT techniques (conventional and global) on the basis of variables and algorithm used. Further, it provides a comparison of MPPT techniques based on the number of control variables involved, types of control strategies, circuitry, and cost of applications, which is possibly useful for MPPT users and researchers in selecting MPPT technique for specific application. The comparison presented in Sec. III of the paper should be helpful in choosing appropriate MPPT technique, on the basis of sensors used, cost, complexity, application, accuracy, and speed.

[1]H. Patel and V. Agarwal, IEEE Trans. Energy Convers. **23**(1), 302–310 (2008).
[2]M. G. Villalva and J. R. Gazoli, IEEE Trans, Power Electron. **24**(5), 1198–1208 (2009).
[3]E. Karatepe, M. Boztepe, and M. Colak, Sol. Energy **81**(8), 977–992 (2007).

[4]M. Veerachary, T. Senjyu, and K. Uezato, IEEE Trans. Aerosp. Electron. Syst. **38**(1), 262–270 (2002).
[5]T. Noguchi, S. Togashi, and R. Nakamoto, IEEE Trans. Ind. Electron. **49**(1), 217–223 (2002).
[6]M. A. S. Masoum, H. Dehbonei, and E. F. Fuchs, IEEE Trans. Energy Convers. **17**, 514–522 (2002).
[7]N. Toshihiko, T. Shigenori, and N. Ryo, in ISIE' 2000, Cholula, Puebla, Mexico (IEEE, 2000), pp. 157–162.
[8]C.-Y. Yang, C.-Y. Hsieh, F.-K. Feng, and K.-H. Chen, IEEE Trans. Circuits Syst., I: Regul. Pap. **59**(7), 1546–1556 (2012).
[9]G. Petrone, G. Spagnuolo, and M. Vitelli, "An Analog Technique for Distributed MPPT PV Applications," IEEE Trans. Ind. Electron. **59**(12), 4713–4722 (2012).
[10]G. Petrone, G. Spagnuolo, and M. Vitelli, IEEE Trans. Ind. Electron. **59**(12), 4713–4722 (2012).
[11]T. Esram and P. L. Chapman, IEEE Trans. Energy Convers. **22**(2), 439–449 (2007).
[12]H. S.-H. Chung, K. K. Tse, S. Y. Ron Hui, C. M. Mok, and M. T. Ho, IEEE Trans. Power Electron. **18**(3), 717–724 (2003).
[13]N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, IEEE Trans. Power Electron. **20**(4), 963–973 (2005).
[14]N. Femia, D. Granozio, G. Petrone, G. Spagnuolo, and M. Vitelli, IEEE Trans. Aerosp. Electron. Syst. **43**(3), 934–950 (2007).
[15]Md. Fahim Ansari, A. Iqbal, S. Chatterji, A. Afzal, 2009 Third International Conference on Power Systems, Kharagpur, India, 27–29 December, Paper Identification Number 25.
[16]A. K. Abdelsalam, A. M. Massoud, S. Ahmed, and P. Enjeti, IEEE Trans. Power Electron. **26**(4), 1010–1021 (2011).
[17]H. Koizumi and K. Kurokawa, "A novel maximum power point tracking method for PV module integrated converter," in *Proc. IEEE 36th Annual Power Electronics Specialists Conference* (IEEE, 2005), pp. 2081–2086.
[18]Y. P. Siwakoti, B. B. Chhetri, B. Adhikary, and D. Bista, "Microcontroller based intelligent DC/DC converter to track Maximum Power Point for solar photovoltaic module," in *IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply (CITRES) 2010* (IEEE, 2010), pp. 94–101.
[19]Y.-C. Kuo, T.-J. Liang, and J.-F. Chen, IEEE Trans. Ind. Electron. **48**(3), 594–601 (2001).
[20]F. Liu, S. Duan, F. Liu, B. Liu, and Y. Kang, IEEE Trans. Ind. Electron. **55**(7), 2622–2628 (2008).
[21]Q. Mei, M. Shan, L. Liu, and J. M. Guerrero, IEEE Trans. Ind. Electron. **58**(6), 2427–2434 (2011).
[22]D. Shmilovitz, IEEE Proc. Electr. Power Appl. **152**(2), 239–248 (2005).
[23]J. W. Kimball and P. T. Krein, IEEE Trans. Power Electron. **23**(5), 2353–2362 (2008).
[24]D. Casadei, G. Grandi, and C. Rossi, IEEE Trans. Energy Convers. **21**(2), 562–568 (2006).
[25]V. V. R. Scarpa, S. Buso, and G. Spiazzi, IEEE Trans. Ind. Electron. **56**(5), 1531–1538 (2009).
[26]P. Wang, H. Zhu, W. Shen, F. H. Choo, P. C. Loh, and K. K. Tan, "A novel approach of maximizing energy harvesting in photovoltaic systems based on bisection search theorem," in *Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC) 2010* (IEEE, 2010), pp. 2143–2148.
[27]R. Shao and L. Chang, in *Canadian Conference on Electrical and Computer Engineering, 2008, CCECE 2008* (IEEE, 2008), pp. 000619–000622.
[28]J. Agrawal and M. Aware, in *2012 IEEE 5th India International Conference on Power Electronics (IICPE)* (IEEE, 2012), pp. 1–6.
[29]S. Kim, M.-B. Kim, and M.-J. Youn. IEEE Trans. Ind. Electron. **53**(4), 1027–1035 (2006).
[30]R. Aghatehrani and R. Kavasseri, IEEE Trans. Sustainable Energy **4**(1), 50,57 (2013).
[31]M. Galvez, E. Bueno, F. J. Rodriguez, F. J. Meca, and A. Rodriguez, in *IEEE Energy Conversion Congress and Exposition, 2009, ECCE 2009* (IEEE, 2009), pp. 48–53.
[32]R. F. Coelho, F. M. Concer, and D. C. Martins, "A MPPT approach based on temperature measurements applied in PV systems," in *9th IEEE/IAS International Conference on Industry Applications (INDUSCON) 2010* (IEEE, 2010), pp. 1–6.
[33]P. Lei, G. Wei, and W. Yinghong, in *International Conference on Sustainable Power Generation and Supply, 2009, SUPERGEN'09* (IEEE, 2009), pp. 1–5.
[34]R. J. Vanderbei, J. Global Optim. **14**(2), 205–216 (1999).
[35]T. L. Nguyen and K.-S. Low, IEEE Trans. Ind. Electron. **57**(10), 3456–3467 (2010).
[36]D. R. Jones, C. D. Perttunen, and B. E. Stuckman, J. Optim. Theory Appl. **79**(1), 157–181 (1993).
[37]F. Gao, D. Li, P. C. Loh, Y. Tang, and P. Wang, "Indirect dc-link voltage control of two-stage single-phase PV inverter," in *Energy Conversion Congress and Exposition (ECCE) 2009* (IEEE, 2009), pp. 1166–1172.
[38]R. Leyva, C. Alonso, I. Queinnec, A. Cid-Pastor, D. Lagrange, and L. Martinez-Salamero, IEEE Trans. Aerosp. Electron. Syst. **42**(1), 249–258 (2006).
[39]S. L. Brunton, C. W. Rowley, S. R. Kulkarni, and C. Clarkson, "Maximum power point tracking for photovoltaic optimization using extremum seeking," in *34th IEEE Photovoltaic Specialists Conference (PVSC) 2009* (IEEE, 2009), pp. 000013–000016.
[40]M. Krstic, IEEE Trans. Autom. Control **47**(2), 318–323 (2002).
[41]J. Hu, J. Zhang, and H. Wu, in IPEMC, September 2009 (2009), pp. 2103–2107.
[42]J. H. Mathews and K. K. Fink, *Numerical Methods Using MATLAB* (Prentice-Hall, Inc., New Jersey, USA, 1999), Vol. 3.
[43]H. Ribeiro, F. Silva, S. Pinto, and B. Borges, "Single stage inverter for PV applications with One Cycle Sampling technique in the MPPT algorithm," in *35th Annual Conference of IEEE Industrial Electronics, 2009 (IECON'09)* (IEEE, 2009), pp. 842–849.
[44]M. Fortunato, A. Giustiniani, G. Petrone, G. Spagnuolo, and M. Vitelli, IEEE Trans. Ind. Electron. **55**(7), 2684–2693 (2008).
[45]N. Khaehintung, C. Kangsajian, P. Sirisuk, and A. Kunakorn, in *International Conference on Power Electronics and Drives Systems (PEDS) 2005* (2005), Vol. 1, pp. 517–521.
[46]Z. Salam and M. Z. Ramli, "A simple circuit to improve the power yield of PV array during partial shading," in IEEE Energy Conversion Congress and Exposition (ECCE) (IEEE, 2012), pp. 1622–1626.
[47]M. Miyatake, M. Veerachary, F. Toriumi, N. Fujii, and H. Ko, IEEE Trans. Aerosp. Electronic Syst. **47**(1), 367–380 (2011).
[48]Q. Fu and N. Tong, in *2010 Second International Conference on Information Technology and Computer Science (ITCS)* (IEEE, 2010), pp. 134–137.
[49]A. Al Nabulsi and R. Dhaouadi, IEEE Trans. Ind. Inf. **8**(3), 573,584 (2012).
[50]S. Gang, G. Wei, P. Lei, G. Rui, and W. Beibei, in Proceedings of the 29th Chinese Control Conference, 29–31 July 2010, Beijing, China.

[51]L. Zhou, Y. Chen, K. Guo, and F. Jia, *IEEE Trans. Power Electron.* **26**(4), 1038–1048 (2011).
[52]D. J. Jefferies, J. H. B. Deane, and G. G. Johnstone, Electron. Commun. Eng. J. **3**(1), 586–592 (1989).
[53]L. Chen and K. Aihara, Neural. Netw. **8**(6), 915–930 (1995).
[54]P. K. Peter and V. Agarwal, IEEE Trans. Power Electron. **27**(12), 4880–4893 (2012).
[55]J. W. Kimball, P. T. Krein, and K. R. Cahill, IEEE Power Electron. Lett. **3**(4), 136–140 (2005).
[56]M. D. Seeman and S. R. Sanders, IEEE Trans. Power Electron. **23**(2), 841–851 (2008).
[57]T. Shun, L. Liu, X. Xiao, X.-C. Zhen, and Y. Yang, in *IEEE 15th International Conference on Harmonics and Quality of Power (ICHQP), 2012* (IEEE, 2012), pp. 733–738.
[58]T. Lei, W. Xu, C. Zeng, D. Dorrell, and X. Yu, in *IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society* (IEEE, 2012), pp. 3334–3339.