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A review on MPPT techniques of PV system under partial shading condition

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ABSTRACT

This paper presents a concise and an organized review of various maximum power point tracking (MPPT) algorithms implemented in the photovoltaic (PV) generation system useable under partial shading condition. Various algorithms, PV modeling techniques, PV array configurations and controller topologies have been widely explored till date. But, every technique always has its advantages as well as disadvantages simultaneously; as a result, a proper literature review is essential while designing a PV generation system (PGS) under partial shading condition. In this paper, the detailed review of MPPT algorithms has been done. The review on MPPT techniques has been classified into mainly four essential groups. The first among them includes all the new MPPT optimization algorithms, the second group includes the hybrid MPPT algorithms, the third category includes new modeling approach, and the fourth category includes the various converter topologies. This paper provides an accessible reference to undertake mass research works in PV systems in the near future under partial shading condition.

1. Introduction

The economic development of a country depends largely on its efficacious electricity supply. In India, the rural electrification program started in the year 1950s with the aim of promoting economic development and improving the quality of life in rural areas. Installations of photovoltaic generation systems (PGS) for clean electricity generation directly from sunlight can help to upgrade the domestic, healthcare, agriculture, education and the enterprise sectors. In this modern era, photovoltaic (PV) technology has the capability to establish a strong expanse in electrifying every corner of the world.

In PGS, it is quite essential to extract the maximum amount of available power from PV panels without getting affected due to the change in irradiance during all day long. But due to partial shading conditions, the power output of PV array reduces drastically and thus the efficiency decreases, configuration complexity increases, and cost increases. In the case of uniform irradiance, the PV array characteristics curve exhibits only one maximum power point which is being tracked using anyone of the long-familiar maximum power point tracking (MPPT) techniques [1–5]. But PV arrays do not get uniform solar radiation throughout the day. During partial shading conditions, the conventional MPPT techniques predominantly fail as multiple maxima points occur due the presence of the bypass diodes, used to forefend hot spots formation in the PV strings. To handle the multiple maxima during partial shading conditions, many modern optimized MPPT techniques are proposed [6]. This paper reappraises the various techniques to extract the maximum amount of power from the shaded PV arrays and is destined to foster more researches in global PV-based power systems. In the former review papers in [7] and [8] the authors primarily had put stress on the conventional MPPT algorithms under both uniform and non-uniform irradiance. In [9], the author mainly accounted the various converter topologies, but a complete realization of all the recent advancements in MPPT for PGS is not being done till date. The conventional MPPT techniques and circuit topologies are not included in this paper. The organization of the paper is as follows: Section 2 provides a brief introduction to the PV characteristics under partial shading condition. Section 3 focuses on new MPPT optimization algorithms under partial shading condition [10–33]. Section 4 discusses the hybridization of earlier MPPT algorithms as discussed in [34–39] and the effectiveness of these hybrid techniques in tracking global maximum power point (GMPP) under partial shading condition. Section 5 reviews on the new modeling approach of PGS as discussed in [40,41]. Section 6 provides the knowledge on various modern PV circuit topologies as discussed in [42–46] that are quite successful in eliminating the problems of partial shading of PV arrays and Section 7 concludes this paper.

2. PV characteristics in both uniform and non-uniform irradiance condition

The output of a PGS is directly affected by the change in solar

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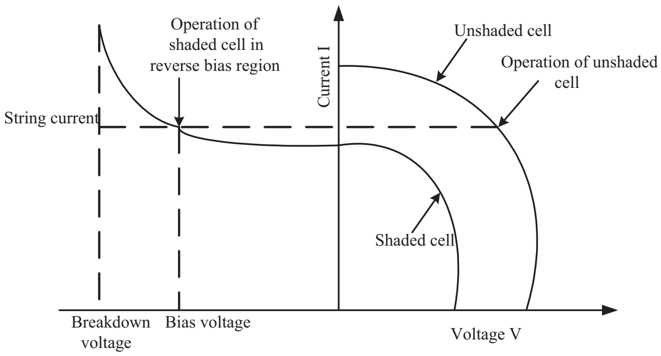

Fig. 1. Current -Voltage characteristic of PV cell during reverse biased region.

irradiance and also the change in temperature. When the PV strings receive uniform insolation from the sun, the power-voltage (P-V) curve shows a unique peak. But when PV array is exhibited to partial shading, it shows multiple peaks on the P-V curve among them there is one global maximum power point (GMPP) and others are called as local maxima power points (LMPPs).

It becomes quite difficult to choose the GMPP from the LMPPs. This is because a snippet of the PV array is able to receive uniform irradiance and operates at the optimum efficiency at the partial shading. The shaded cells (which receive less irradiance or no irradiance) operate along with a reverse biased voltage in order to give the same current as given by the unshaded cells because a constant amount of current should flow in every module in the series configuration of PV modules. The insolation level is proportional to short circuit current of PV cell. Fig. 1 shows how the shaded cells are operating in reverse biased voltage region for providing the same current as provided by the unshaded cells. Fig. 2 shows the conduction of bypass diode takes place under shading condition when Eq. (1) is satisfied.

$$V_2 - \sum_{i=1}^{n} V_i \geq V_{DO,} \qquad i \neq 2 \tag{1}$$

Where V_{DO} is the forward voltage drop of the diode [6].

The bypass diodes as shown in Fig. 3(b) are used to provide an alternate path to the current flow if the partial shading condition occurs in the PV array. The P-V curve shown in Fig. 3(c) depicts the multiple maxima during partial shading condition. As the conventional MPPT optimization algorithms fail to differentiate between the GMPP and the LMPPs, so many new modern MPPT optimization algorithms are developed using the evolutionary algorithms, differential algorithms, artificial neural networks, artificial intelligence techniques, new topology of converters, new reconfiguration of PV modules, and new PV modeling techniques.

3. Maximum power point tracking optimization algorithms under partial shading condition

Various MPPT optimization techniques are being addressed in a stochastic order in this section.

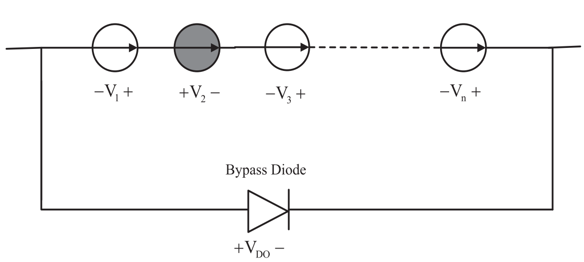

Fig. 2. Bypass Diode conduction when one cell is shaded.

3.1. Grey wolf optimization

The grey wolf optimization (GWO) is a meta-heuristic approach strongly inspired by optimizing the attacking technique used by the grey wolves while hunting. This technique is quite capable of imitating the leadership hierarchical order and also the hunting proficiency of grey wolves. There are mainly four types of grey wolves-alpha (α), beta (β), delta (δ) and omega (ω) which are being employed in order to simulate the leadership hierarchy properly. In the mathematical model of this bio-inspired technique, the fittest solution is assumed to be α. Then, β and δ are considered to be the second and third best solution, ω is denoted as the rest of the candidate solutions. There are mainly three steps for GWO, such as hunting, chasing and tracking of the prey by forming a group, then encircling the prey and then finally attacking the prey. This overall hunting mechanism is implemented while designing the GWO for executing optimization problems in MPPT for PV modules. The hunting technique of the grey wolves is guided by α clans which are termed as leaders and are followed by the β clans. The main duty of the δ and ω is to take care of all the wolves that are wounded in the entire pack. The GWO in [10] is being combined with the direct duty cycle control (DCC) to keep duty cycle constant at MPP to reduce steady state oscillations. The flowchart of GWO algorithm is shown in Fig. 4. The total hunting mechanism of grey wolves described here is modeled by the help of the following equations:

$$\overrightarrow{E} = |\overrightarrow{C}.\ \overrightarrow{X_P}(t) - \overrightarrow{X_P}(t)| \tag{2}$$

$$\overrightarrow{X}(t+1) = \overrightarrow{X_P}(t) - \overrightarrow{F}.\overrightarrow{E} \tag{3}$$

Here t denotes the current iteration; *E, F* and *C* represent the coefficient vectors. X_p represent the position vector of the hunting prey and X denotes the position vector for the Grey wolf. The vector *F* and *C* are computed as follows:

$$\overrightarrow{F} = 2\overrightarrow{a}.\ \overrightarrow{r_1} - \overrightarrow{a} \tag{4}$$

$$\overrightarrow{C} = 2.\overrightarrow{r_2} \tag{5}$$

Where a decreases linearly from 2 to 0 and $\overrightarrow{r_1}$ and $\overrightarrow{r_2}$ vector values in [0,1]. At MPP the duty cycle is normalized at a fixed value to reduce the steady-state oscillation and power loss that exists in conventional MPPT optimization algorithms. In order to implement the GWO MPPT, the duty cycle d is considered as the grey wolf. Therefore Eq. (3) modified as Eq. (6) and the GWO fitness function is calculated as Eq. (7).

$$d_i(k+1) = d_i(k) - F.\ E \tag{6}$$

$$P(d_i^k) > P(d_i^{k-1}) \tag{7}$$

Here *P* denotes power, *d* as duty cycle, i is the number of the current individual grey wolves, k represents the iteration count. The major advantages of GWO technique are higher tracking efficiency with elimination of transient and steady state oscillations.

3.2. Firefly algorithm with an updated β coefficient

The author in [12] has proposed a simplified firefly algorithm (SFA) with an updated β coefficient which is mostly used in order to track MPPT of a PV system under the condition of partial shading. The SFA algorithm is a modification of the firefly algorithm (FA) [11]. In FA, the first position of the firefly is randomized with the use of variables γ (the light absorption coefficient) and α (random coefficient) while in the SFA the initial position of the firefly is selected in between 0 and 1 and the above two variables are hence not required. The optimization equation of SFA is represented as:

$$X_i^{t+1} = X_i^t + \beta(X_j - X_i) \tag{8}$$

where X_i and X_j signifies the position of i (less brighter firefly) and j (more brighter firefly) and β is the firefly attractiveness factor. In

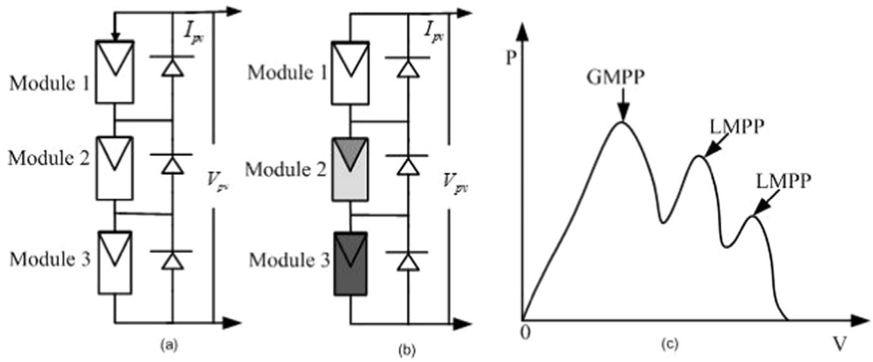

Fig. 3. A single PV string showing (a) uniform irradiance (b) non-uniform irradiance patterns (c) the P-V peaks consisting of GMPP and LMPPs.

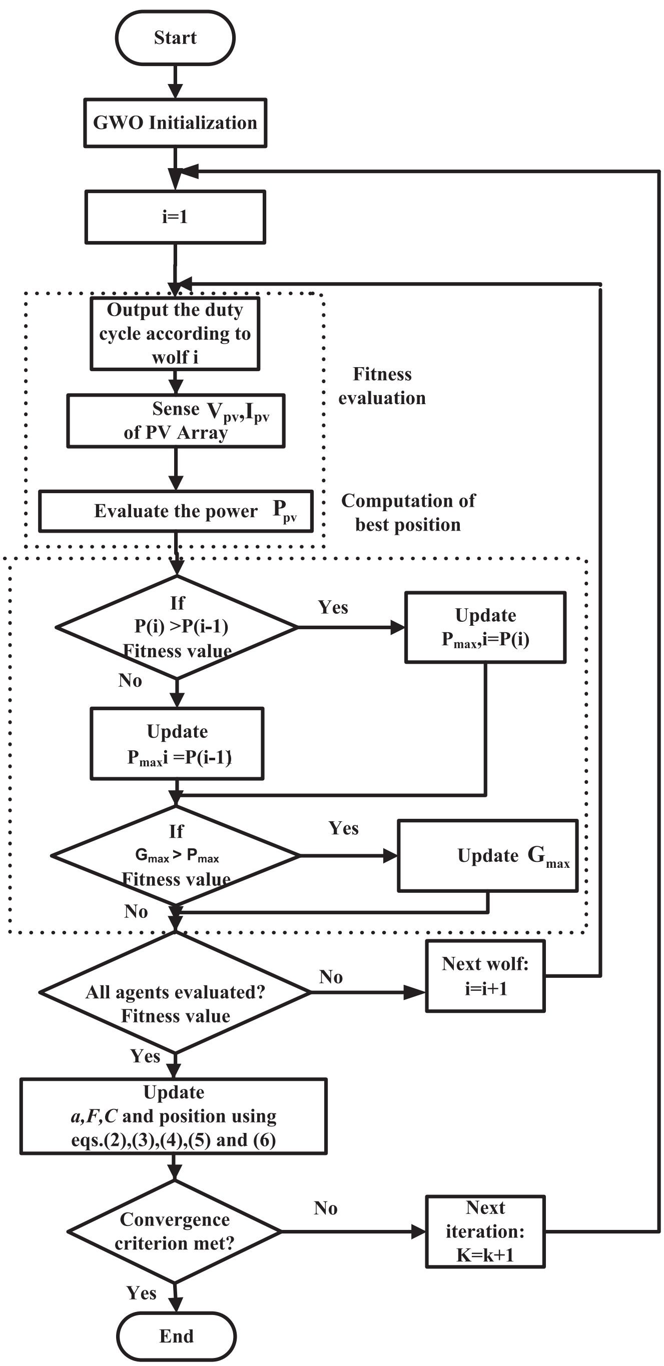

Fig. 4. Flowchart of Grey wolf optimization technique.

MPPT, the objective function of SFA is to get the desired photovoltaic output power and the firefly position represents the duty cycle D. In the paper [12], the value of β coefficient is updated in every iteration for faster convergence and accurate result.

3.3. Ant colony optimization

The ant colony optimization (ACO) is a probabilistic algorithm as discussed in [13,14] which helps to find out the optimized output based on the food searching behavior of the ants. This method is a modified form of PSO method. After sensing the power from the PV module, it provides the optimized duty cycle which is further being applied to the converter. ACO is able to reduce the number of LMPPs of the I-V curve and is used in both centralized type as well as distributed type MPPT controllers.

3.4. Artificial bee colony based algorithm

Artificial bee colony (ABC) algorithms is mainly a bio-inspired method discussed in [15,16] which is simple, uses very few controlled parameters and the algorithm convergence criteria are not dependent on initial conditions of the system. It is a swarm based meta-heuristic algorithm capable of solving multidimensional as well as multimodal optimization problems very easily. The artificial bees, classified mainly into three important groups- they are the employed bees, the onlooker bees and last the scouts. The bee which currently searches the food or exploits the food production source is called as an employed bee, a bee that waits in the hive to make decisions to choose a food source is called as an onlooker and the scout bee is used to carry the random search for a new food source. All three groups work together by communication and coordination to get the optimal solution in lesser time. Here duty cycle is the food position and maximum power as the food source of ABC algorithm. The ABC optimization algorithm as shown in Fig. 5 is divided into four phases as discussed in [16].

For implementing ABC in MPPT for PV system, the duty cycle for the DC to DC converter is calculated as follows

$$d_e = d_{min} + \ rand\,[0,\ 1](d_{max} - d_{min}) \tag{9}$$

$$newd_e = d_e + \phi_e(d_e - d_k) \tag{10}$$

where d_e (current duty cycle), $d_{\min}$ (minimum value of duty cycle), $d_{\max}$ (maximum value of duty cycle), ϕ_e (is a constant) between [−1,1] and d_k (previous duty cycle). The ABC tracks MPP with good accuracy and efficiency under partial shading conditions.

3.5. Deterministic particle swarm optimization

The deterministic particle swarm optimization (DPSO) is a modified PSO algorithm which has better tracking capability than conventional PSO. In conventional PSO [47–49], if a change in the duty cycle for two successive iteration count is low, then the subsequent change in

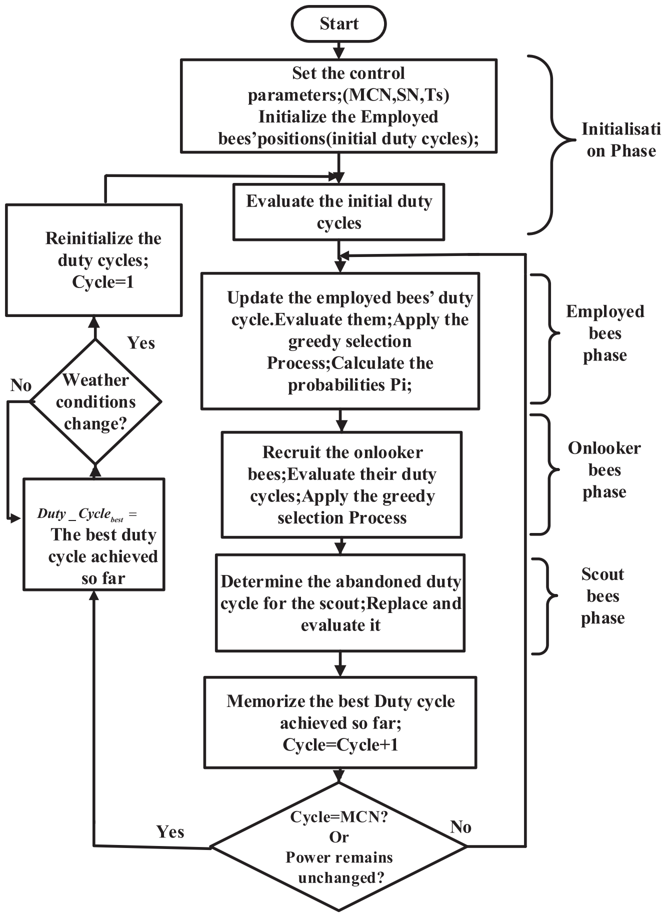

Fig. 5. Flowchart of artificial bee colony optimization.

duty cycle results in more iteration number to reach the final solution. Also, in PSO, if a particle is away from the best position then a large change in velocity is required which may make the particle to escape from the GMPP. The DPSO proposed in [17,18] makes the optimization simpler by removing the number of acceleration factor in velocity equation and limiting the velocity factor according to the distance between two peaks. The algorithm operates usually in two modes, the local and the global mode. The global mode gets activated when the partial shading occurs. At global mode, the algorithm shifts to DPSO subroutine and during local mode variable step size perturbation is used. For global mode, the range of duty cycle is calculated as follows:

$$d_{\min} = \frac{\sqrt{\eta bbR_{L\ \min}}}{\sqrt{R_{PV\ \max}} + \sqrt{\eta bbR_{L\ \min}}} \tag{11}$$

$$d_{\max} = \frac{\sqrt{\eta bbR_{L\ \max}}}{\sqrt{R_{PV\ \min}} + \sqrt{\eta bbR_{L\ \max}}} \tag{12}$$

where $d_{\min}$ represents the minimum duty cycle, $d_{\max}$ represents the maximum duty cycle, ηbb represents the converter's efficiency, $R_{L\ \min}$ as well as $R_{L\ \max}$ are the minimum and maximum values for the load connected at output, $R_{PV\ \min}$ as well as $R_{PV\ \max}$ represents the reflective impedances of the PV array. The DPSO has a greater advantage than normal PSO as the number of iteration is reduced, tuning effort is reduced and the problem of random search is also minimized.

3.6. Improved curve tracer

Curve Tracer is used mainly in the MPPT techniques which are software based as discussed in [19]. It consists of two stages; one is mainly the boost converter's stage, and the other stage contains a duty-modulated load resistor (DMLR) along with a hysteretic modified self-control circuit. The boost converter is used to push the panel operating point to a load operating point. The improved curve tracer as proposed in [19] has mainly two operating modes, the first one is the fixed resistor (FR) and the second is the modulated resistor (MR) mode. In the FR mode, the curve tracer acts like a conventional boost V-I curve tracer whereas in the MR modes, DMLR modulates equivalent resistance of the load switch. The improved curve tracer has a simple structure; has low implementation cost and it has no tracing limitation.

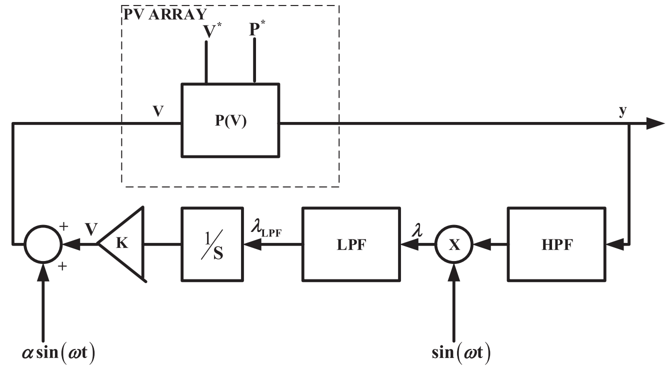

Fig. 6. Extremum seeking controller.

3.7. Improved extremum-seeking based MPPT

The extremum-seeking control (ESC) as discussed in [20–23] mainly consists of a control strategy applied to the nonlinear system that has local minimum and maximum points. The algorithm as shown in Fig. 6 mainly employs the injection of a small perturbing signal called as the dither signal ($\alpha\ \sin(\omega t)$). The proposed ESC-based algorithm operates in a cyclic process to iterate the array voltage according to the count of the maximum possible power peaks. The main theory behind the proposed method is to find the GMPP by comparing the powers as well as the power gradients in every segment after the end of each of the cycle. As a result, this method is used to identify a non-global MPP segment; the process continues till the GMPP is calculated.

3.8. Simulated annealing method

The simulated annealing (SA) optimization method follows the process of metal annealing. For finding the main GMPP of a given PV system, SA discussed in [24] uses parameters such as an initial temperature, the final temperature and the nominal cooling rate. For each temperature, the algorithm does several perturbations at the operating voltage and measure the corresponding energy. The energy that is measured is compared with current reference energy. If the new operating point has greater energy, then it will be accepted as the new operating point. If the new operating point has less energy than the reference operating point, then it may still be accepted depending upon the acceptance probability P_r as follows:

$$P_r = \exp\left[\frac{P_k - P_i}{T_k}\right] \tag{13}$$

where, P_k denotes the power at the recent voltage, P_i denotes the power at the earlier operating point and T_k denotes the current system temperature. The SA algorithm comprises of a cooling schedule of either static or adaptive type. The geometric cooling schedule is given as

$$T_k = \alpha T_{k-1} \tag{14}$$

where T_k denotes the temperature at kth step, T_{k-1} denotes the temperature at $(k-1)$th step and α (cooling rate) denotes a constant (α < 1). The flow chart of SA method is shown in Fig. 7.

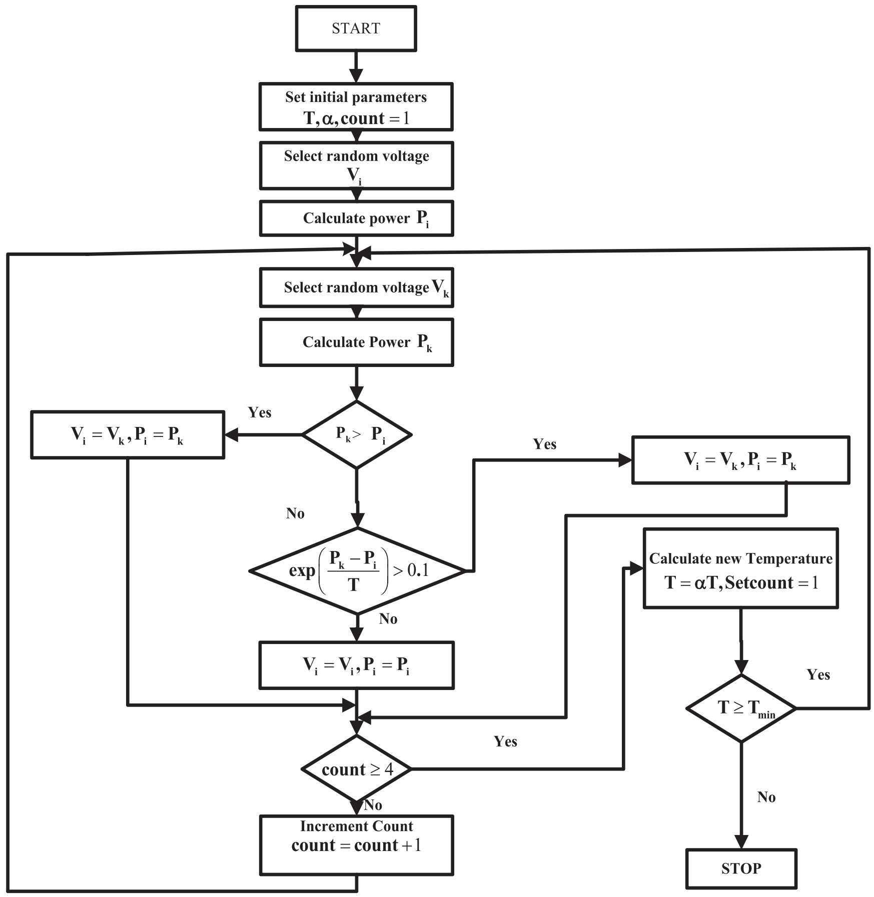

Fig. 7. Flowchart of the simulated annealing (SA) method.

3.9. Variable step Newton-Raphson (VSNR) method through model predictive control

The variable step newton-raphson (N-R) method uses the model predictive control (MPC) which is mainly an alternative to the classical control methods. It has many advantages like fast dynamic response, simple concept, easy implementation, have high speed, good reliability and also avoids unacceptable oscillations. In the proposed scheme in [25], MPC is applied using a boost converter. The main purpose of the MPC is to estimate the future behavior of the controlled variables to minimize the cost function. The cost function is being evaluated twice for each switching states. It is being proved that despite the variations in output voltage, the proposed model predictive control circuit with boost converter is successful in regulating the load current.

3.10. Variable step size perturb and observe method

It is a modified form of the conventional perturb and observe (P & O) method as discussed in [26]. At the start of the algorithm the reference voltage ($Vref$) is set at about 0.80*Voc, where Voc is the open circuit voltage of the array. It has two mode of operation i.e voltage search mode and MPP search mode. Voltage search mode bring the operating point near the reference voltage and MPP search mode do the fine tuning near MPP. The peak is tracked first by applying modified P & O algorithm. If there is an indication of partial shading GMPP tracking is performed. In this method, unnecessary tracking of GMPP is avoided. The proposed algorithm takes shorter time to track the MPP as compared to [3,46,50].

3.11. Optimal P & O control technique for MPPT based on least square support vector machines algorithm

This control strategy as discussed in [29] combines the perturb and observe (P & O) method with the least square support vector machines algorithm (LS-SVM). The LS-SVM method is employed for perturbation of voltage when the irradiation is changed. The major merit of LS-SVM identification technique in the PV application is that nonlinearities are not considered as shown in Fig. 8. As the MPP changes due to the change in illumination, the output voltage starts increasing slowly by a proper voltage step size δV at every period of P & O control. When δV is gradually small due to the minimized oscillations, the convergence rate is reduced to get the optimal result.

3.12. Dynamic population size differential evolution (DynNP-DE) algorithm

In this technique as discussed in [30] at the beginning higher size of population is being needed to make thorough evaluation of the function's landscape. The entire population of a community is considered at first and later on by dividing the population into multiple groups the best individuals among all is being sorted. The fittest candidate among all iterations (current and previous) will survive for next iteration. To make the optimization simpler, the population size for next generation is mainly reduced to half of the initial size. In MPPT, the control parameter (voltage or the duty cycle) is being randomly generated in between specified upper and lower limit. The size of the population is then reduced for doing the mutation, crossover and selection process. The DynNP- DE has good accuracy in searching global MPP with higher convergence speed and gives the optimal result.

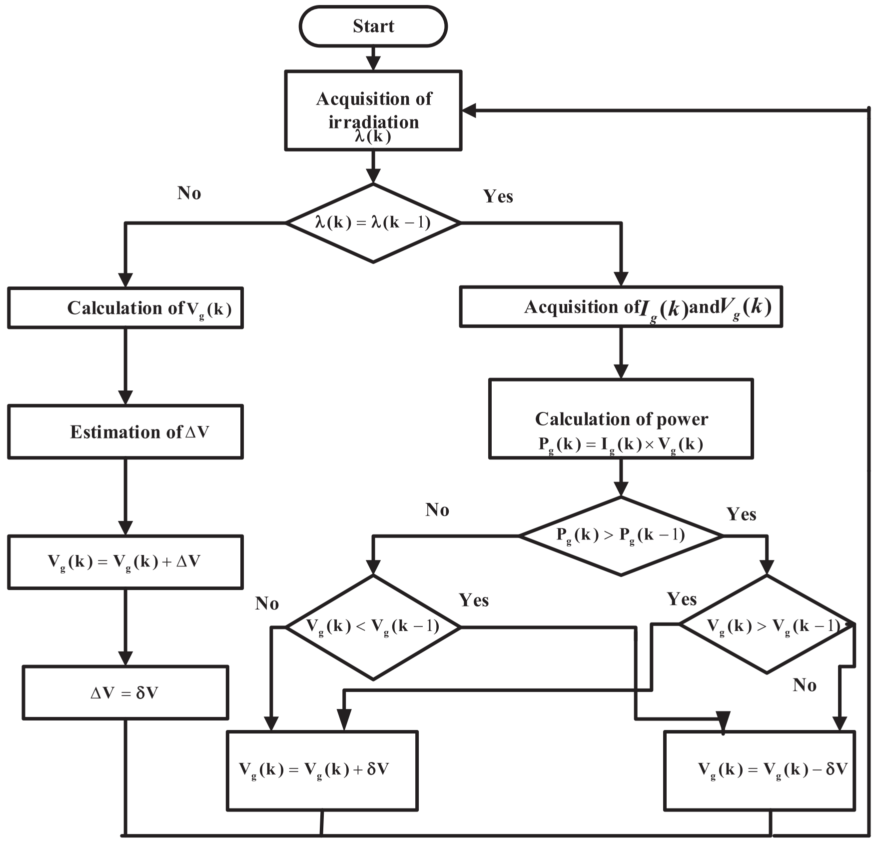

Fig. 8. Flowchart of optimal perturb and observe method.

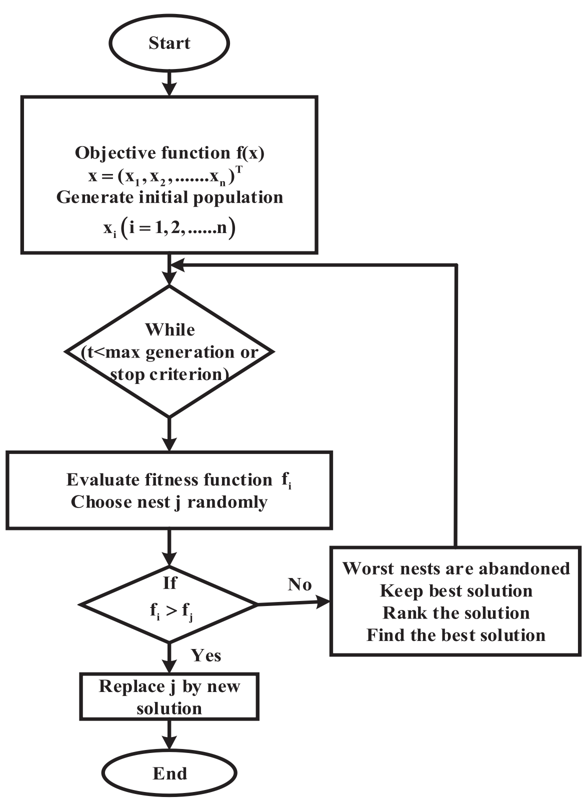

Fig. 9. Flowchart of cuckoo search method.

3.13. Chaotic search

The chaos word can be defined easily in a simple term as randomness that occurs due to the sensible nature of system for a small change in initial conditions. Hence, this predefined feature in [31] is used to search for the optimization of MPPT in PGS. In PGS, voltage is the optimization variable and power is the fitness function. There are two methods for optimization, single carrier and the multiple carriers. Single carrier search is always not feasible as it takes a much longer time to converge to the MPP while the multiple carriers (dual-carrier) is able to improve the precision, efficiency and also the system robustness. By consecutive iterations, the searching zone decreases and stops when it reaches the threshold value and provide a faster convergence.

3.14. Cuckoo search

The cuckoo search (CS) method in [32,33] is a bio-inspired parasitic reproduction scheme of the cuckoo birds. In CS, searching steps for a nest is characterized by levy flight mechanism. A levy flight is mainly random walk from which the step sizes are being extracted for levy distributions. Due to levy's flight mechanism, step sizes for CS are relatively larger than the normal PSO. It accelerates faster convergence. As the particles move nearer to the MPP, the step size consecutively gets smaller and finally reduced to zero. The flow chart for CS is shown in Fig. 9.

4. Hybridization of conventional MPPT algorithms

This section provides the importance of hybrid MPPT algorithms in comparison to conventional MPPT algorithms for MPP tracking under partial shading condition.

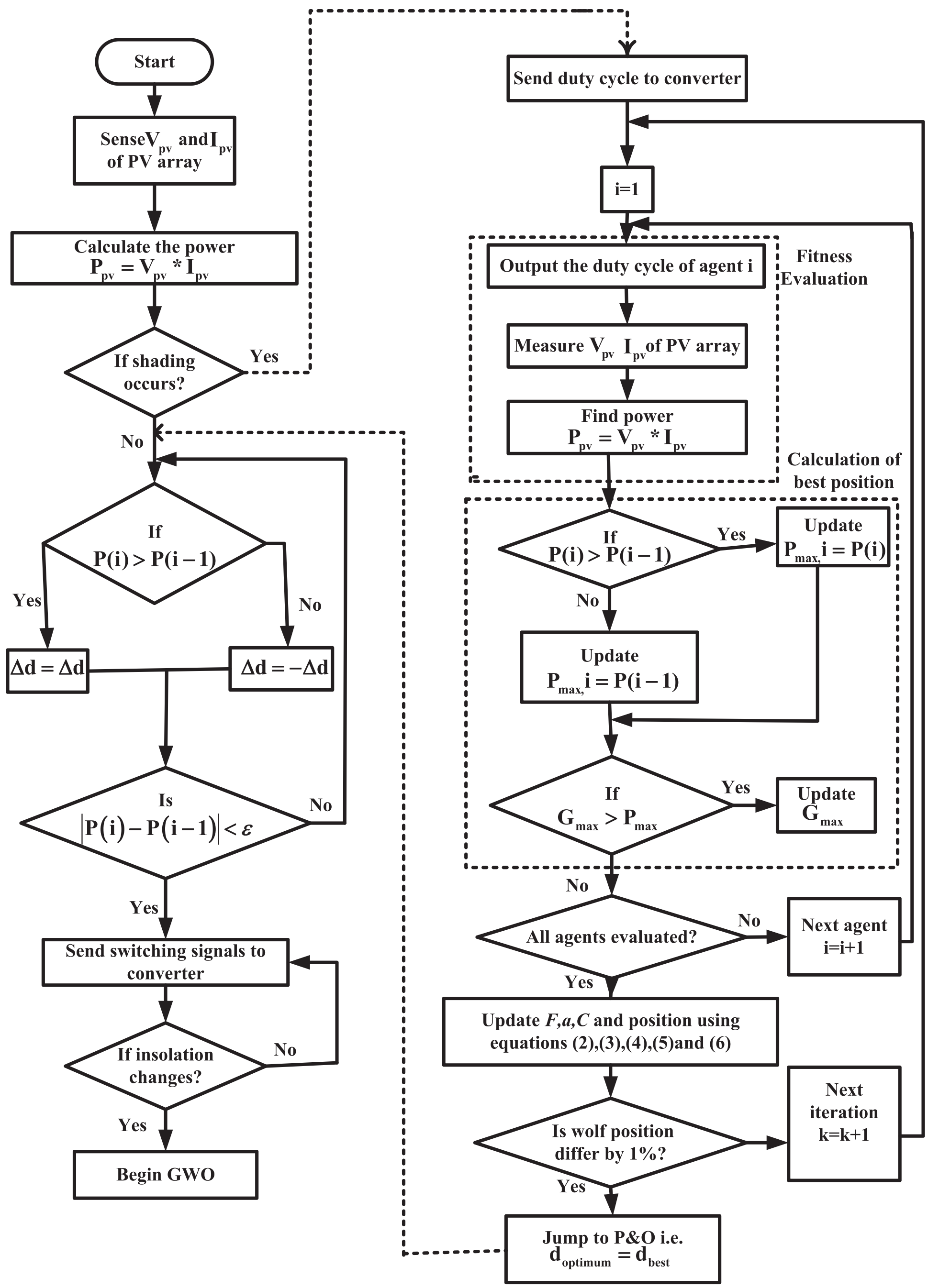

Fig. 10. Flowchart of hybrid GWO and P & O algorithm.

4.1. Hybrid GWO and P & O MPPT algorithm

The hybrid MPPT as discussed in [34] combines GWO with P & O to extract maximum power from the PV array efficiently under partial shading condition. The GWO technique [10] has been hybridized with the conventional P & O method in which GWO works in the initial phase of MPPT and later on P & O operates for faster convergence to GMPP. By doing this the search space of GWO has been reduced and computational burden decreases. In this method, the position of wolves denotes the duty cycle of the converter used. The use of PI controller in the MPPT implementation is completely eliminated. The major advantage of this method when compared to the normal GWO and P & O method is that it has higher tracking capability, faster convergence speed and higher efficiency. The flowchart of hybrid GWO and P & O algorithm is shown in Fig. 10.

4.2. Hybrid PSO-PI based MPPT algorithm using adaptive sampling time strategy

The hybrid PSO-PI MPPT controller as discussed in [35] uses particle swarm optimization(PSO) approach to locate the global peak (GP). Once, the GP is traced, the algorithm is switched to the proportional-integral(PI) mode to track the slow change in the GP location. An adaptive sampling time strategy (ASTS) is applied to accelerate the convergence towards the GP. The hybrid PSO-PI improves the performance of the standalone PSO controller. For the PSO controller, the objective function f is chosen to be output power of PV array, p_{ibest} is the best power, the equation is given by-

$$f(x_i^k) > f(p_{ibest}) \tag{15}$$

An initial vector x^1 of four agents $[V_1, V_2, V_3, V_4]$ is defined-

$$x^1 = [V_1, V_2, V_3, V_4] \tag{16}$$

These agents are applied successively as a reference voltage to the converter. At GP, the derivative of $P(t)$ with respect to $V(t)$ becomes zero. Hence, a control variable $e(t)$ is defined as:

$$e(t) = \frac{dP(t)}{dV(t)} \tag{17}$$

Since, $e(t)$ disappears at the MPP, the objective of the PI controller is to nullify the slope $e(t)$

$$V_{mp}(t) = K_p.\ e(t) + K_I.\ \int e(t)dt \tag{18}$$

The inequality (19) must be satisfied to re-initialize the search process.

$$\begin{cases} \frac{|P_{i+1} - P_i|}{P_i} \geq 10\% \\ |V_{i+1} - V_i| \leq 0.5V \end{cases} \tag{19}$$

Where i+1 is the actual value and i is the previous value.

In the hybrid PSO-PI method, the tracking speed is increased and the tracking error is greatly reduced.

4.3. Hybridized simulated annealing and perturb and observe method (P & O)

The hybridized simulated annealing and perturb and observe method takes the advantages of both SA and P & O as proposed in [36]. Since, the conventional P & O method is incapable to locate the global maxima and SA method is unsuccessful to perform the continuous search, so both of them are combined in the hybrid MPPT method. SA is used for global search and P & O is used for local search. As a result, the performance of tracking is easily improved as compared with the independent working of each algorithm as shown in Fig. 11. When the P & O method is tracking around MPP, only a small change in power should occur for each small step. The equation is given by-

$$\frac{|P_{pv,new} - P_{pv,last}|}{P_{pv,last}} > threshold \tag{20}$$

where $P_{pv,new}$ is the new generated power of PV module and $P_{pv,last}$ is the last generated power of PV module. The threshold is a small value nearly 2%. The optimization technique takes a constant threshold value irrespective of any change in irradiation.

4.4. P & O combined with PSO

The hybridization of P & O along with PSO is proposed in [37,38]. At the beginning of the algorithm PSO is used for global search and then P & O is used at the final stage. PSO method as discussed in [51–54] is employed for searching the GMPP. The hybrid method finds the GMPP in a shorter time than normal PSO method. In [37] different shading cases are being tested to verify the efficacy of the proposed method. The boost converter with interleaved topology is used to reduce ripple current, improve reliability and increase the efficiency. The proposed method tracks the GMP easily and has faster convergence time and also better dynamic response than normal PSO method.

4.5. Hybrid DEPSO method

The DEPSO is a hybridization of differential evolutionary (DE) algorithm and PSO. The DEPSO algorithm as discussed in [39] is able to avoid local optima by combining DE operator with PSO. As the insolation changes, there is sharp fluctuation in power with respect to the location of qth particle. The condition given in Eq. (21) must be satisfied for the reinitialization of the algorithm. The condition shows the minimum variation in output power to run the algorithm to find new MPP.

$$\left| \frac{J(X_{q+1}) - J(X_q)}{J(X_q)} \right| > \Delta P \tag{21}$$

Where $J(X_q)$ is the output power of PV panel. The proposed DEPSO is successful in distinguishing the GMPP from LMPPs during mismatch-

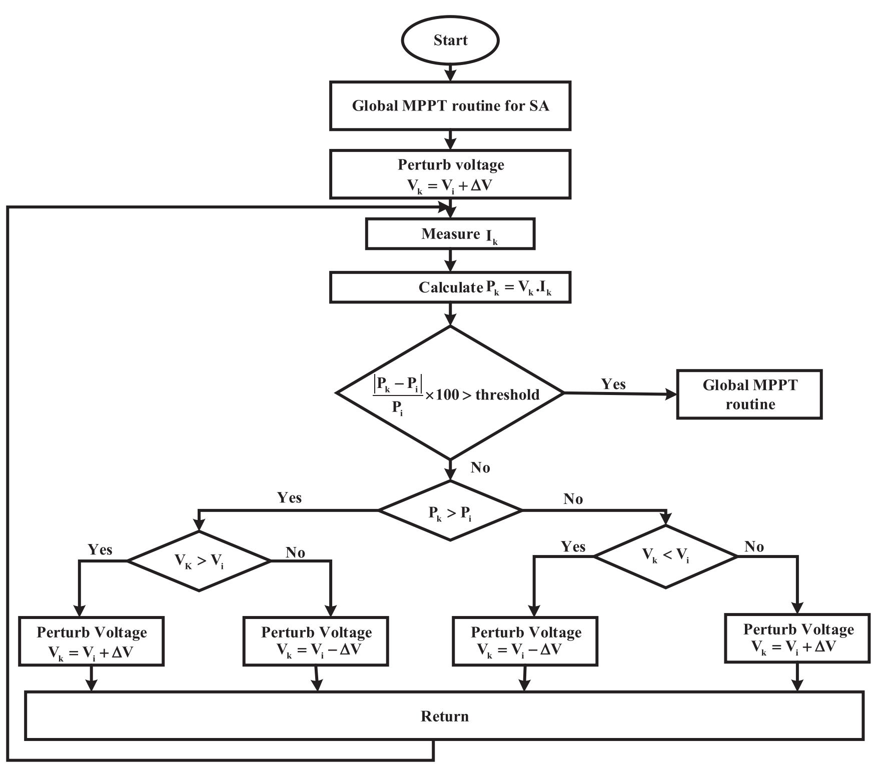

Fig. 11. Flowchart of hybrid SA and P & O algorithm.

Table 1
Comparison of various optimization techniques applied for MPPT.

Name of technique and reference number	Year of publication	Control strategy	Input parameters	Output parameters	Cost	Applications (Stand-alone/ Grid)	Converter used (DC/DC or (DC/AC)
Grey wolf Optimization Technique [10]	2016	Bio-Inspired Evolutionary Algorithm	V_{pv}, I_{pv}	Duty Cycle	High	Stand-alone	DC-DC
β-Firefly Algorithm [11]	2014	Bio-Inspired Evolutionary Algorithm	V_{pv}, I_{pv}	Duty Cycle	Low	Stand-alone	DC-DC
Ant Colony Optimization [14]	2014	Probabilistic Algorithm	V_{pv}, I_{pv}	Duty Cycle	Low	Stand-alone	DC-DC
Artificial Bee Colony Optimization [16]	2015	Bio-Inspired Evolutionary Algorithm	V_{pv}	Duty Cycle	High	Stand-alone	DC-DC
Deterministic Particle Swarm Optimization [18]	2014	Modified PSO	V_{pv}, I_{pv}	Duty Cycle	Low	Stand-alone	DC-DC
Improved Curve Tracer [19]	2014	Software Based	V_{pv}, I_{pv}	Duty Cycle	High	Stand-alone	DC-DC
Improved Extremum Seeking Control [22]	2014	Cyclic Algorithm	V_{pv}, P_{pv}	V_{out}	High	Both	Both
Simulated Annealing Algorithm [24]	2016	Metal Annealing Technique	T_k	$P_{\max}$	High	Stand-alone	DC-DC
Variable-Step Newton-Raphson Method [25]	2013	Modified P & O	V_{pv}, I_{pv}	$P_{\max}$	Low	Stand-alone	DC-DC
Variable Step Perturb and observe method [26]	2016	Modified P & O	V_{pv}, I_{pv}	Duty Cycle	Low	Stand-alone	DC-DC
Optimal Perturb and Observe method [29]	2015	Modified P & O	V_{pv}	V_{out}	Low	Stand-alone	DC-DC
Dynamic Population size Differential Evolution [30]	2014	Differential Algorithm	V_{pv}	$P_{\max}$	Low	Stand-alone	DC-DC
Chaotic Search [31]	2011	Bio-Inspired Evolutionary Algorithm	V_{pv}, I_{pv}	Duty Cycle	High	Stand-alone	DC-DC
Cuckoo Search [32,33]	2013	Bio-Inspired Evolutionary Algorithm	V_{pv}, I_{pv}	Duty Cycle	Low	Stand-alone	DC-DC
Hybrid GWO and P & O [34]	2016	Bio-Inspired Computational Algorithm	V_{pv}, I_{pv}	Duty Cycle	High	Stand-alone	DC-DC
Hybrid PSO and PI method [35]	2015	Adaptive Sampling Time Strategy	V_{pv}, I_{pv}	Duty Cycle	High	Stand-alone	DC-DC
Hybrid SA and P & O method [36]	2015	Metal Annealing Technique	V_{pv}, T_k	$P_{\max}$	High	Stand-alone	DC-DC
Hybrid PSO and P & O [37,38]	2015	Evolutionary Algorithm	V_{pv}, I_{pv}	Duty Cycle	Low	Stand-alone	DC-DC
Hybrid DEPSO method [39]	2015	Hybrid Evolutionary Algorithm	V_{pv}, I_{pv}	Duty Cycle	Low	Stand-alone	DC-DC

Table 2
Summary of merits and demerits of various MPPT methods.

Name of technique	Merits	Demerits
Grey wolf Optimization Technique	Higher tracking efficiency, no transient and steady state oscillations, robust, fewer parameters needed for adjustment	Computational complexity, Large search space, high cost
β-Firefly Algorithm	Faster convergence, accurate results, high tracking efficiency, never fall on LMPP	Beta coefficient is updated in every iterations which is difficult to do, give poor result than other swam based algorithm
Ant Colony Optimization	Convergence does not depend upon the initial position of the sample, Simple control, low cost, robust to various shading pattern	Four evolutionary parameters required to be optimized at once, which is difficult to do simultaneously, complex calculation
Artificial Bee Colony Optimization	Simple, uses fewer control parameters, convergence is independent of initial conditions	Slow tracking, complex, May fall on LMPP because of fewer control parameters
Deterministic Particle Swarm Optimization	Convergence speed and accuracy is improved, Removes the random number in the accelerations factor of the conventional PSO velocity equation. MPPT structure is simple compared to conventional PSO. Efficiency 99.5%	Excessive amount of calculation,computationally complex, dependent on initial conditions
Improved Curve Tracer	Simple structure, implementation cost is low, no tracing limitation near V_{oc}	May fall at LMPP
Improved Extremum Seeking Control	It does not require a system model, higher overall efficiency, Robust, implementation is inexpensive	Need large number of samples before finding all the peaks. Thus tracking speed is low with steady state oscillations.
Simulated Annealing Algorithm	Converge accurately to GMPP, fewer parameters required	Computational complexity, oscillation at MPP, reinitialization required with change in weather condition
Variable-Step Newton-Raphson Method	Good dynamic response, flexible, less fluctuation around MPP	Complex calculation
Variable Step Perturb and observe method	Quickly tracks global peak among local peaks	Two stage tracking, oscillation around MPP
Optimal Perturb and Observe method	Reduced oscillation, faster convergence, LS-SVM constructed offline with reduced training data	Complex control structure, May fall at LMPP
Dynamic Population size Differential Evolution	Small population size, Faster convergence	Complex calculation, May fall on LMPP because of reduction of population size dynamically
Chaotic search	Search efficiency increases for multiple MPP Track maximum power quickly and accurately under sudden change in insolation. Robust and reliable	Complex algorithm. Tracking speed depend upon chosen step size.
Cuckoo Search	Efficient randomization, convergence speed is very high, robust and fewer tuning parameter required. High efficiency	Complex calculation, tracking time depend upon levy flight, deterioration of convergence speed and accuracy.
Hybrid GWO and P & O	Superior tracking performance, reduced oscillation, reduction of search space, computational overhead decreases, tracking efficiency nearly 99.9%	Difficult control structure, costly, difficult to implement
Hybrid PSO and PI method	Tracking speed increase, tracking error reduced	Oscillations around MPP, difficult control structure, costly, proper tuning of K_P and K_I required
Hybrid SA and P & O method	SA is used for global search and P & O used for local search, tracking performance improved, fast tracking	Reinitialization required with change in weather condition, difficult to optimize the parameters of SA, suitable threshold detection is difficult
Hybrid PSO and P & O	Search space is reduced, faster convergence to GMPP, reduced oscillations in output power, voltage and current	Complex control structure, hardware implementation is costly, Convergence cannot be guaranteed if GMPP located outside the search zone
Hybrid DEPSO method	Reliable, system independent, accurate tracking under partial shading condition with high tracking speed	Complex calculation, large number of parameters need to be selected for optimization

ing conditions. The DEPSO is system independent MPPT technique and presence of random numbers helps this algorithm to keep its meta-heuristic approach and also find the GMPP in any partially shaded condition.

As discussed above, comparison of various optimization techniques applied for MPPT of PV system under partial shading condition is given in Table 1. Merits and demerits of different optimization MPPT techniques are presented in Table 2.

5. New PV modeling approach under partial shading condition

5.1. Fast power peaks estimator during partially shaded PV systems

The author in [40] proposed a new modeling method for PV array under a partially shaded condition to track the MPP. Due to the complexity and more time consuming problems, no model based MPPT was developed earlier for partially shaded PV system. The homogeneous irradiance PV systems discussed in [55–61] represent the modeling of PV system. The proposed modeling approach as discussed in [40] rely on three governing rules for the identification of power peaks in partially shaded PV system. The Lambert model as discussed in [40] is based on the following equation:

$$V = (I_{ph} + I_s)R_{sh} - (R_s + R_{sh})I - a \times Lambert\,(W)$$
$$W = \frac{R_{sh} * I_s}{a} e^{\left(\frac{R_{sh}.(I_{ph}+I_s-I)}{a}\right)} \tag{22}$$

where I_{ph}, I_s, R_s, R_{sh} and N_s are photovoltaic current, saturation current, series resistance, shunt resistance and the number of series PV cells in PV module. The method is successful in determining the power peaks without doing simulation of entire power curve and is able to save computational time.

5.2. Sub-module integrated converter based PV system

The sub-module integrated converter based PV system is proposed in [41] to reduce power loss by reducing the effect of I-V mismatch among the modules comprising the PV array. PV modules as proposed in [62–66] is based on ideal single diode model. In the proposed technique in [41] a comprehensive control strategy is developed to coordinate the control of distributed MPPT (DMPPT), PV sub-module voltage regulation (PSVR) and dc-link voltage regulation (DCLVR) under partial shading conditions. Taking into account several case studies, the effectiveness of the proposed model is verified and simulated. The author has taken 42 sub-modules to verify the efficiency of system under partial shade and various PV mismatch conditions.

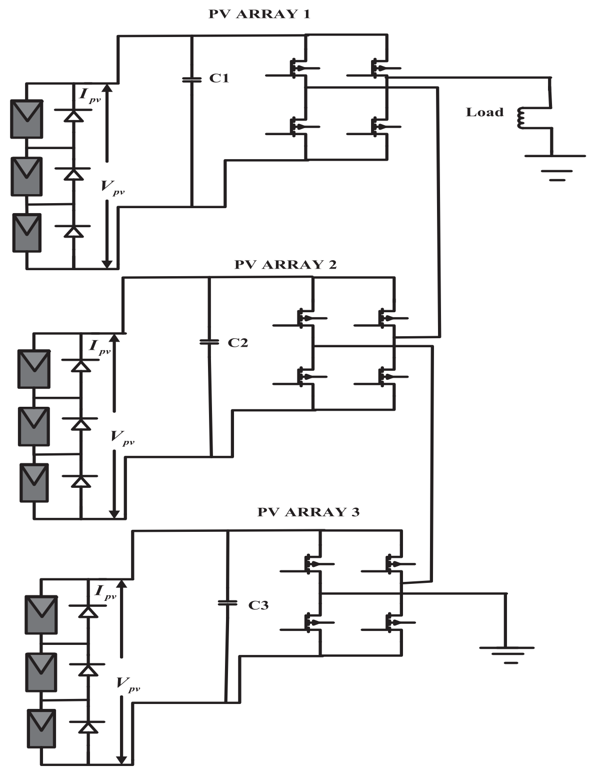

Fig. 12. Topology of CHB photovoltaic system.

6. Modern PV circuit topologies

6.1. Cascaded H-Bridge (CHB) photovoltaic system

The modularity of CHB converter [67–73] has been used to enhance the MPP tracking performance of PV system. The author in [42] has used a 7-level CHB converter for a 3.3 kW peak solar PV system for MPP tracking. The effectiveness of the proposed MPPT scheme is compared under different scenarios. The advantages of this method are that tracking speed is faster with good steady state performance. As no extra sensors are required, hence model complexity is low. The major advantage is that during partial shading or with change in temperature, the control decision is only made by present quantities and do not depend on previous quantities as a result the misled of MPPT does not occur. The topology of CHB photovoltaic system is shown in Fig. 12.

6.2. DC-DC converter topology with a direct control method

The DC-DC push-pull converter with direct control MPP algorithm is proposed in [43]. It can extract power directly from the MPP algorithm easily and is able to track the MPPs very accurately with change in irradiance. For maintaining MPP, the converter control requires two loops. The push-pull converter proposed in [43] requires less components and uses the direct control scheme. From the experimental results, it is being concluded that the proposed control system is capable of tracking available PV panel output power for every time, hence reduces the power loss and system cost.

6.3. Multi-level PV inverter with PV groups for independent MPPT control

As discussed in [44], series-connected PV modules are divided into multiple segments. As a result, each segment became the input dc source for each unit of the multi-level inverter (MLI). The voltage of every DC unit in the MLI is easily adjustable independently without

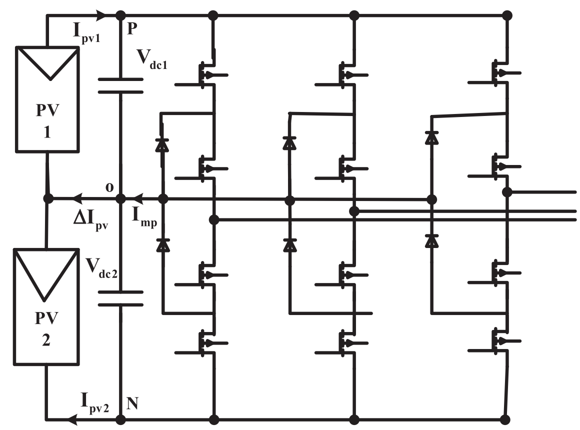

Fig. 13. Topology of multilevel PV inverter.

compromising the output AC voltage distortion. The topology as discussed in [74–77] i.e. three-level neutral point clamped (NPC) inverter comprising of two PV groups has been used in [44]. The topology of multilevel PV inverter system is shown in Fig. 13. For controlling each dc unit separately, a dc unit voltage feedback control strategy which is based on the zero-sequence injection is implemented. For high non-uniform irradiance condition, system stability and power generation get affected. Improvisations of algorithms as well as new circuit topologies are required for extending the utilization of MLI in PGS.

6.4. Shunt-series compensation

The use of dc to dc converter discussed in [78–82] is called as DMPPT is the most efficient MPPT extraction method. In the shunt-series compensation technique as discussed in [45], a current-compensated converter is connected in shunt with each PV string. Also, a voltage-compensating converter as discussed in [71] is connected in series along with each PV string. This makes each PV module to operate at exact MPP and deliver maximum power. A combined shunt series compensating technique is proposed in [45], for operating each module at MPP. The compensation of the voltage difference between the strings is called as "compensating power dedicated converter". For the unified shunt and series compensating nature of the converter, in the proposed scheme [45], the compensated voltage is produced by compensating converter. When the shunt-series compensation are unified together, it makes each PV module to be able to operate at exact MPP and delivers maximum power to the given load but fails during unlikely shade condition.

6.5. Variable interleaving cascaded DC-DC converter

In the variable interleaving algorithm, as proposed in [46], the DC link voltage is used. Under partial shading condition, the first harmonic frequency component remains in the DC link while applying the fixed interleaving technique. But in the variable interleaving technique, the first harmonic component in the DC link voltage can be completely eliminated. Due to the presence of interleaving technique, it is able to reduce the components of the cascaded DC-DC converter. The efficiency of this converter is near about 99% which is much more than discussed in [44,46,83–88] and due to small size of the converter the system is light and low cost. The topology of variable interleaving cascaded DC-DC converter is shown in Fig. 14. Different converter topologies with their efficiency are given in Table 3.

7. Challenges and further studies

The primary challenge in tracking maximum power from partially

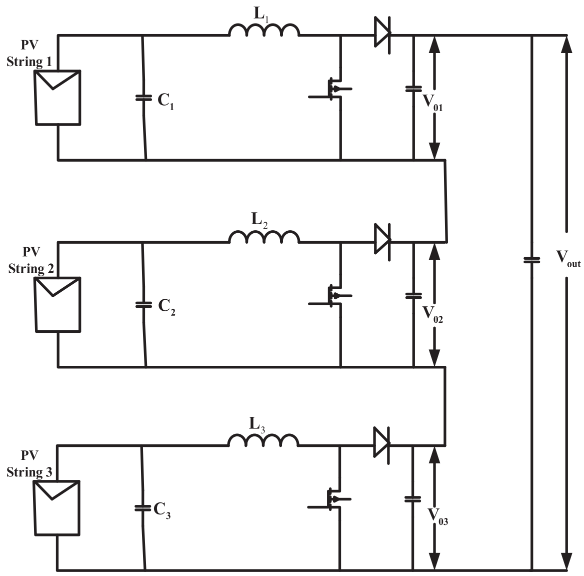

Fig. 14. Topology of variable interleaving cascaded DC-DC converter.

Table 3
Comparison of various converter topologies.

Converter topology with reference number	Efficiency
Buck Converter [83]	92%
Boost Converter [84]	97–98.2%
Buck-Boost Converter [85]	99.5%
Cuk Converter [86]	> 96%
SEPIC Converter [87]	> 90%
Flyback Converter [88]	> 92%
Variable Interleaving Cascaded DC-DC Converter [46]	99%
Multilevel PV Converter [44]	> 90%

shaded PV array is that it's accurate mathematical model under shading condition is not available. It is tough to predict the global peak beforehand under partial shading condition. PV module parameters changes when insolation and temperature vary, which is not considered while modeling it to avoid the complexity of the model. Under partial shading condition, I-V mismatch among the modules forming the array causes significant energy loss of the array. To avoid hotspot formation and reverse current flow, bypass and blocking diodes are used which causes multiple maxima point in the P-V characteristic. To mitigate partial shading effect on PV array characteristics, many array reconfiguration techniques such as series-parallel (SP), total cross tied (TCT), bridge-linked (BL), honey-comb (HC), hybrid array reconfiguration are available in the literature [89,90]. Unfortunately none of the discussed methods have considered the array reconfiguration in their proposed MPPT. Many of the swarm based techniques need large number of iterations to locate the MPP which increases the computational complexity. The major challenges in all swarm based techniques are selection of search space, population size, initial condition and control parameters. Selection of control parameters varies from problem to problem and it affects the computational behavior of the optimization algorithm. Hybrid techniques give better result than individual MPPT techniques but it has complicated control structure.

After reviewing the MPPT techniques under partial shading condition, the following points are proposed for further studies.

Although many metaheuristic optimization techniques have already been explored and used for MPPT of PV system under PSC, still many techniques are there to explore such as teaching learning based optimization (TLBO), JAYA optimization, bat swarm optimization (BSO), shuffled frog leaping (SFL), evolutionary programming (EP), invasive weed optimization (IWO), gravitational search algorithm (GSA), biogeography-based optimization (BBO), grenade explosion method (GEM), seeker optimization algorithm (SOA), krill herd optimization (KHO), water cycle algorithm (WCA), harmony search algorithm (HS), and evolution strategy may be used for better tracking and recommended for future research. Under partial shading condition evolutionary algorithm (EA) plays a promising role. However, there is scope for improving EA, by selecting appropriate control parameters and narrowing down the search space, so that computational time and complexity can be reduced. Control structure should be simple and inexpensive so that it can be designed with ease. A number of hybrid techniques should come up, which can take the advantages of both conventional and soft computing MPPT techniques. Different metaheuristic optimization techniques are available for MPP tracking for different PV array rating, size and different shading conditions. So it is very difficult to categorize them by common benchmarked indices. However, it is still possible to classify them according to their tracking speed, algorithm complexity, cost, hardware implementation, steady state oscillation and their applications. To reduce the cost, complexity in hardware implementation and measurement error, use of current sensorless MPPT is encouraged. Finding simpler, faster and cheaper MPP tracker with better efficiency and reliability is recommended.

8. Conclusion

This review article provides brief descriptions of all the modern MPPT algorithms those are being used in software and hardware platform. It deals with the MPPT optimization techniques those are mainly focused on partial shading conditions of PGS. This review has included many recent hybrid techniques apart from the new MPPT algorithms. PV modeling approach under partial shading condition is discussed for better tracking with easy identification of power peaks. Many modern PV circuit topologies considered to enhance the MPP tracking performance of the PV system. Merits and demerits of different optimization techniques are discussed to choose a suitable MPPT under partial shading condition. From the various methods discussed in this paper it is very difficult to conclude which method is the better one. The choice of MPPT depends upon the application, hardware availability, cost, convergence time, accuracy and reliability of the system. Considering the importance of MPPT under partial shading condition, it can be concluded that there is lots of research scope to find a suitable MPPT which can improve the output efficiency of PGS. This review is expected to provide a very beneficial tool to all the researchers working on PV system and also to all the industries excelled in generating an efficient, clean and sustainable energy to the mankind.

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References

[1] Esram T, Chapman PL. Comparison of photovoltaic array maximum power point tracking techniques. IEEE Trans Energy Convers 2007;22:439–49. http://dx.doi.org/10.1109/TEC.2006.874230.
[2] Subudhi B, Pradhan R. A comparative study on maximum power point tracking techniques for photovoltaic power systems. IEEE Trans Sustain Energy 2013;4:89–98.
[3] Lyden S, Haque ME, Gargoom A, Negnevitsky M. Review of maximum power point tracking approaches suitable for PV systems under partial shading conditions. In: Proceedings of the Australas univ power eng conf; 2013. p. 1–6. http://dx.doi.org/10.1109/AUPEC.2013.6725344.
[4] El-Khozondar HJ, El-Khozondar RJ, Matter K, Suntio T. A review study of photovoltaic array maximum power tracking algorithms. Renew Wind Water Sol 2016;3:3. http://dx.doi.org/10.1186/s40807-016-0022-8.
[5] Engineering IP, Conference O, Jewel T. The application of soft computing

techniques to improve the performance of maximum power point tracker for PV system during partial shading. In: Proceedings of the 2014 8th int power eng optim conf (PEOCO 2014); 2014. p. 237–42. http://dx.doi.org/10.1109/PEOCO.2014.6814432.
[6] Bidram A, Davoudi A, Balog RS. Control and circuit techniques to mitigate partial shading effects in photovoltaic arrays. IEEE J Photovolt 2012;2:532–46. http://dx.doi.org/10.1109/JPHOTOV.2012.2202879.
[7] Ishaque K, Salam Z. A review of maximum power point tracking techniques of PV system for uniform insolation and partial shading condition. Renew Sustain Energy Rev 2013;19:475–88. http://dx.doi.org/10.1016/j.rser.2012.11.032.
[8] Liu L, Meng X, Liu C. A review of maximum power point tracking methods of PV power system at uniform and partial shading. Renew Sustain Energy Rev 2016;53:1500–7. http://dx.doi.org/10.1016/j.rser.2015.09.065.
[9] Rajesh R, Carolin Mabel M. A comprehensive review of photovoltaic systems. Renew Sustain Energy Rev 2015;51:231–48. http://dx.doi.org/10.1016/j.rser.2015.06.006.
[10] Mohanty S, Subudhi B, Ray PK. A new MPPT design using grey Wolf optimization technique for photovoltaic system under partial shading conditions. IEEE Trans Sustain Energy 2016;7:181–8. http://dx.doi.org/10.1109/TSTE.2015.2482120.
[11] Sundareswaran K, Peddapati S, Palani S. MPPT of PV systems under partial shaded conditions through a colony of flashing fireflies. IEEE Trans Energy Convers 2014;29:463–72. http://dx.doi.org/10.1109/TEC.2014.2298237.
[12] Safarudin YM, Priyadi A, Purnomo MH, Pujiantara M. Maximum power point tracking algorithm for photovoltaic system under partial shaded condition by means updating β firefly technique. In: Proceedings of the 6th int conf inf technol electr eng (ICITEE 2014); 2014. p. 1–4. http://dx.doi.org/10.1109/ICITEED.2014.7007942.
[13] Jiang LL, Maskell DL, Patra JC. A novel ant colony optimization-based maximum power point tracking for photovoltaic systems under partially shaded conditions. Energy Build 2013;58:227–36. http://dx.doi.org/10.1016/j.enbuild.2012.12.001.
[14] Jiang LL, Maskell DL. A uniform implementation scheme for evolutionary optimization algorithms and the experimental implementation of an ACO based MPPT for PV systems under partial shading. In: Proceedings of the IEEE symp comput intell appl smart grid (CIASG 2014); 2014. p. 1–8. http://dx.doi.org/10.1109/CIASG.2014.7011560.
[15] Sundareswaran K, Sankar P, Nayak PSR, Simon SP, Palani S. Enhanced energy output from a PV system under partial shaded conditions through artificial bee colony. IEEE Trans Sustain Energy 2015;6:198–209. http://dx.doi.org/10.1109/TSTE.2014.2363521.
[16] soufyane Benyoucef A, Chouder A, Kara K, Silvestre S, sahed OA. Artificial bee colony based algorithm for maximum power point tracking (MPPT) for PV systems operating under partial shaded conditions. Appl Soft Comput 2015;32:38–48. http://dx.doi.org/10.1016/j.asoc.2015.03.047.
[17] Ishaque ZS K. A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition. IEEE Trans Ind Electron 2013;60:3195–206.
[18] Divya K, Sugumaran G. Intelligent control technique for MPPT of PV system. In: Proceedings of the IEEE int caracas conf devices, circuits syst (ICCDCS 2014); 2014. p. 1–5. http://dx.doi.org/10.1109/ICDCSyst.2014.6926164.
[19] Ramaprabha R, Jubair SH, Suhas K, Lokesh A. Development of improved curve tracer for photovoltaic system under partial shaded conditions. In: Proceedings of the 2014 int conf circuits, power comput technol (ICCPCT 2014); 2014. p. 585–9. http://dx.doi.org/10.1109/ICCPCT.2014.7054857.
[20] Lei P, Li Y, Seem J. Sequential ESC based global MPPT control for photovoltaic array with variable shading. IEEE Trans Sustain Energy 2011;2:348–58.
[21] Heydari-doostabad H, Keypour R, Khalghani MR, Khooban MH. A new approach in MPPT for photovoltaic array based on extremum seeking control under uniform and non-uniform irradiances. Sol Energy 2013;94:28–36. http://dx.doi.org/10.1016/j.solener.2013.04.025.
[22] Elnosh A, Khadkikar V, Xiao W, Kirtely JL. An improved Extremum-Seeking based MPPT for grid-connected PV systems with partial shading. IEEE Int Symp Ind Electron 2014:2548–53. http://dx.doi.org/10.1109/ISIE.2014.6865021.
[23] Leyva R, Olalla C, Zazo H, Cabal C, Cid-Pastor A, Queinnec I, et al. MPPT based on sinusoidal extremum-seeking control in PV generation. Int J Photoenergy 2012;2012. http://dx.doi.org/10.1155/2012/672765.
[24] Lyden S, Haque ME. A simulated annealing global maximum power point tracking approach for PV modules under partial shading conditions. IEEE Trans Power Electron 2016;31:4171–81. http://dx.doi.org/10.1109/TPEL.2015.2468592.
[25] Hosseini SH, Farakhor A, Khadem Haghighian S Novel algorithm of MPPT for PV array based on variable step Newton-Raphson method through model predictive control. In: Proceedings of the 2013 13th int conf control autom syst (ICCAS 2013); 2013. p. 1577–82. http://dx.doi.org/10.1109/ICCAS.2013.6704181.
[26] Ahmad J, Spertino F, Leo P Di, Ciocia A. A variable step size perturb and observe method based MPPT for partially shaded photovoltaic arrays 2. Characteristics of photovoltaic arrays under partial shading conditions; 2016. 10–2.
[27] Mohapatra A, Nayak B, Mohanty KB. Current based novel adaptive P & O MPPT algorithm for photovoltaic system considering sudden change in the irradiance. In: Proceedings of the 2014 IEEE int. conf. power electron. drives energy syst. (PEDES, 2014); 2014. http://dx.doi.org/10.1109/PEDES.2014.7042032.
[28] Khaehintung N, Wiangtong T, Sirisuk P. FPGA implementation of MPPT using variable step-size P & O algorithm for PV applications. In: Proceedings of the 2006 int symp commun inf technol; 2006. p. 212–15. http://dx.doi.org/10.1109/ISCIT.2006.340033.
[29] Dahhani O, Jouni A El, Sefriti B, Boumhidi I. Optimal perturb and observe control for MPPT based on least square support vector machines algorithm. Intell Syst Comput Vis 2015:1–7.
[30] Tajuddin MFN, Ayob SM, Salam Z. Global maximum power point tracking of PV system using dynamic population size differential evolution (DynNP-DE) algorithm. In: Proceedings of the 2014 IEEE conf energy conversion (CENCON 2014); 2014. p. 254–9. http://dx.doi.org/10.1109/CENCON.2014.6967511.
[31] Zhou L, Chen Y, Guo K, Jia F. New approach for MPPT control of photovoltaic system with mutative-scale dual-carrier chaotic search. IEEE Trans Power Electron 2011;26:1038–48. http://dx.doi.org/10.1109/TPEL.2010.2078519.
[32] Ahmed J, Salam Z. A soft computing MPPT for PV system based on Cuckoo Search algorithm. In: Proceedings of the int conf power eng energy electr drives; 2013. p. 558–62. http://dx.doi.org/10.1109/PowerEng.2013.6635669.
[33] Ahmed J, Salam Z. A Maximum Power Point Tracking (MPPT) for PV system using Cuckoo Search with partial shading capability. Appl Energy 2014;119:118–30. http://dx.doi.org/10.1016/j.apenergy.2013.12.062.
[34] Mohanty S, Subudhi B, Ray PK. A grey wolf assisted perturb & observe MPPT algorithm for a photovoltaic power system. IEEE Trans Energy Convers 2016;8969. http://dx.doi.org/10.1109/TEC.2016.2633722.
[35] Kermadi, Mostefa, Berkouk EM. A hybrid PSO-PI based maximum power point tracking algorithm using adaptive sampling time strategy. In: Proceedings of the 4th int conf electr eng (ICEE, 2015); 2015. p. 1–6.
[36] Lyden S, Haque ME. A hybrid simulated annealing and perturb and observe method for maximum power point tracking in PV systems under partial shading conditions. In: Proceedings of the 2015 Australas univ power eng conf challenges futur grids (AUPEC 2015); 2015. http://dx.doi.org/10.1109/AUPEC.2015.7324803.
[37] Lian KL, Jhang JH, Tian IS. A maximum power point tracking method based on perturb-and-observe combined with particle swarm optimization. IEEE J Photovolt 2014;4:626–33. http://dx.doi.org/10.1109/JPHOTOV.2013.2297513.
[38] Sundareswaran K, Vignesh kumar V, Palani S. Application of a combined particle swarm optimization and perturb and observe method for MPPT in PV systems under partial shading conditions. Renew Energy 2015;75:308–17. http://dx.doi.org/10.1016/j.renene.2014.09.044.
[39] Seyedmahmoudian M, Rahmani R, Mekhilef S, Maung Than Oo A, Stojcevski A, Soon TK, et al. 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;6:850–62. http://dx.doi.org/10.1109/TSTE.2015.2413359.
[40] Mahmoud Y, El-Saadany EF. Fast power-peaks estimator for partially shaded PV systems. IEEE Trans Energy Convers 2016;31:206–17. http://dx.doi.org/10.1109/TEC.2015.2464334.
[41] Khan O, Xiao W. An efficient modeling technique to simulate and control submodule-integrated PV system for single-phase grid connection. IEEE Trans Sustain Energy 2016;7:96–107. http://dx.doi.org/10.1109/TSTE.2015.2476822.
[42] Farivar G, Agelidis VG, Member S, Hredzak B. A simple perturb and observe MPPT scheme for cascaded H-bridge based photovoltaic system; 2013.
[43] Gaikwad DD, Chavan MS, Gaikwad MS Hardware implementation of DC-DC converter for MPPT in PV applications. In: Proceedings of the 2014 IEEE glob conf wirel comput networking (GCWCN 2014); 2015. p. 16–20. http://dx.doi.org/10.1109/GCWCN.2014.7030839.
[44] Xie L, Qi J, Weng G, Zhang Y Multi-level PV inverter with photovoltaic groups independent MPPT control. In: Proceedings of the 2014 17th int conf electr mach syst (ICEMS 2014); 2015. p. 829–34. http://dx.doi.org/10.1109/ICEMS.2014.7013599.
[45] Sharma P, Agarwal V. Maximum power extraction from a partially shaded PV array using shunt-series compensation. IEEE J Photovolt 2014;4:1128–37. http://dx.doi.org/10.1109/JPHOTOV.2014.2323698.
[46] Kashani MG, Mobarrez M, Bhattacharya S. Variable interleaving technique for photovoltaic cascaded DC-DC converters. In: Proceedings of the 40th annual Industrial Electron Conf; 2014. p. 5612–7. http://dx.doi.org/10.1109/IECON.2014.7049359.
[47] Ishaque K, Salam Z, Taheri H, Shamsudin A. Maximum power point tracking for PV system under partial shading condition via particle swarm optimization. In: Proceedings of the 2011 IEEE appl power electron colloquium (IAPEC 2011). 2; 2011. p. 5–9. http://dx.doi.org/10.1109/IAPEC.2011.5779866.
[48] Liu YH, Huang SC, Huang JW, Liang WC. A particle swarm optimization-based maximum power point tracking algorithm for PV systems operating under partially shaded conditions. IEEE Trans Energy Convers 2012;27:1027–35. http://dx.doi.org/10.1109/TEC.2012.2219533.
[49] Ishaque K, Salam Z, Amjad M, Mekhilef S. An improved particle swarm optimization (PSO)-based MPPT for PV with reduced steady-state oscillation. IEEE Trans Power Electron 2012;27:3627–38. http://dx.doi.org/10.1109/TPEL.2012.2185713.
[50] Liu CX, Liu LQ An improved perturbation and observation MPPT method of photovoltaic generate system. In: Proceedings of the 2009 4th IEEE conf ind electron appl (ICIEA 2009); 2009. p. 2966–70. http://dx.doi.org/10.1109/ICIEA.2009.5138752.
[51] Jumpasri N, Pinsuntia K, Woranetsuttikul K, Nilsakorn T, Khan-ngern W. Improved particle swarm optimization algorithm using average model on MPPT for partial shading in PV array. In: Proceedings of the 2014 int electr eng congr; 2014. p. 1–4. http://dx.doi.org/10.1109/iEECON.2014.6925856.
[52] Chen K, Tian S, Cheng Y, Bai L. An improved MPPT controller for photovoltaic system under partial shading condition. IEEE Trans Sustain Energy 2014;5:978–85. http://dx.doi.org/10.1109/TSTE.2014.2315653.
[53] Badis A, Mansouri MN, Sakly A. PSO and GA-based maximum power point tracking for partially shaded photovoltaic systems. In: Proceedings of the 7th int renew energy congr (IREC 2016); 2016. http://dx.doi.org/10.1109/IREC.2016.7478923.

[54] Dhar S, Sridhar R, Mathew G. Implementation of PV cell based standalone solar power system employing incremental conductance MPPT algorithm. In: Proceedings of the IEEE int conf circuit, power comput technol (ICCPCT 2013); http://dx.doi.org/10.1109/ICCPCT.2013.6528926.

[55] Boussaibo A, Kamta M, Kayem J, Toader D, Haragus S, Maghet A. Characterization of photovoltaic pumping system model without battery storage by MATLAB/Simulink. In: Proceedings of the 2015 9th int symp adv top electr eng (ATEE 2015); 2015. p. 774–80. http://dx.doi.org/10.1109/ATEE.2015.7133907.

[56] Al-Masri H, Alhuwaishel F, Alismail F, Sabeeh S, Kanakri H. Investigation of MPPT for PV applications by mathematical model. In: Proceedings of the 15th 2015 IEEE int conf environ electr eng (EEEIC 2015) – Conf Proc; 2015. p. 1800–5. http://dx.doi.org/10.1109/EEEIC.2015.7165446.

[57] Lentine AL, Nielson GN, Okandan M, Sweatt WC, Cruz-campa JL, Gupta V. Optimal cell connections for improved shading , reliability , and spectral performance of microsystem enabled photovoltaic (Mepv) modules; 2010. p. 3048–54.

[58] Macabebe EQB, Sheppard CJ, van Dyk EE. Parameter extraction from I-V characteristics of PV devices. Sol Energy 2011;85:12–8. http://dx.doi.org/10.1016/j.solener.2010.11.005.

[59] Villalva M, Gazoli J, Filho E. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans Power Electron 2009;24:1198–208. http://dx.doi.org/10.1109/tpel.2009.2013862.

[60] Villalva MG, Gazoli JR, Ruppert EF. Modeling and circuit-based simulation of photovoltaic arrays. Braz J Power Electron 2009;14:1244–54.

[61] Nayak BK, Mohapatra A, Mohanty KB. Parameters estimation of photovoltaic module using nonlinear least square algorithm: a comparative study. In: Proceedings of the 2013 IEEE annu. India conf. (INDICON 2013); 2013. http://dx.doi.org/10.1109/INDCON.2013.6726120.

[62] Gao L, Dougal RA, Liu S, Iotova AP. Parallel-connected solar PV system to address partial and rapidly fluctuating shadow conditions. IEEE Trans Ind Electron 2009;56:1548–56. http://dx.doi.org/10.1109/TIE.2008.2011296.

[63] El-dein MZS, Member S, Kazerani M, Member S, Salama MMA. An optimal total cross tied interconnection for reducing mismatch losses in photovoltaic arrays; 2013. 4. p. 99–107.

[64] Zhang MZM, Wu JWJ, Zhao HZH. The application of slide technology in PV maximum power point tracking system. In: Proceedings of the fifth world congr intell control autom (IEEE Cat No04EX788); 2004. 6. p. 5591–4. http://dx.doi.org/10.1109/WCICA.2004.1343805.

[65] Rtiz-Rivera EI, Peng F. A novel method to estimate the maximum power for a photovoltaic inverter system. In: Proceedings of the IEEE annu power electron spec conf (PESC Rec); 2004. 3. p. 2065–9. http://dx.doi.org/10.1109/PESC.2004.1355436.

[66] Hilloowala RM, Sharaf AM. A rule-based fuzzy logic controller for a PWM inverter in photo-voltaic energy conversion scheme. In: Proceedings of the IEEE ind appl soc annu meet (Conf Rec 1992); 1992. p. 762–9. http://dx.doi.org/10.1109/IAS.1992.244319.

[67] Hilloowala RM, Sharaf AM. A rule-based fuzzy logic controller for a PWM inverter in a stand alone wind energy conversion scheme. IEEE Trans Ind Appl 1996;32:57–65. http://dx.doi.org/10.1109/28.485813.

[68] Hilloowala RM, Sharaf AM. No Title. A rule-based fuzzy log. controll. A PWM invert. A stand alone wind energy convers. scheme. In: Proceedings of the IEEE conference; 1993, p. 2066–73. http://dx.doi.org/10.1109/IAS.1993.299150.

[69] Kim H, Kim S, Kwon C-K, Min Y-J, Kim C, Kim S-W. An energy-efficient fast maximum power point tracking circuit in an 800-μW photovoltaic energy harvester. IEEE Trans Power Electron 2013;28:2927–35. http://dx.doi.org/10.1109/TPEL.2012.2220983.

[70] Uprety S, Member S, Lee H, Member S. A 0.4 W-to-21 W fast-transient global-search- algorithm based integrated photovoltaic energy harvester with 99% GMPPT efficiency and 94% power efficiency. IEEE J Solid-State Circuits 2016;51:2153–67.

[71] Zubair Mehmood, Yumna Bilal, Muniba Bashir AA. Performance analysis of MPPT charge controller with single and series/parallel connected PV panels; 2016. p. 278–82.

[72] Pradhan R, Subudhi B, Ray PK. A real-time linearized maximum power point tracker for photovoltaic system. In: Proceedings of the int conf power electron drive syst; 2013. p. 962–7. http://dx.doi.org/10.1109/PEDS.2013.6527157.

[73] Mishra S, Sekhar PC. Ts fuzzy based adaptive perturb algorithm for MPPT of a grid connected single stage three phase VSC interfaced PV generating system. In: Proceedings of the IEEE power energy soc gen meet; 2012. p. 1–7. http://dx.doi.org/10.1109/PESGM.2012.6345397.

[74] Sun D, Ge B, Liang W, Abu-Rub H, Peng FZ. An energy stored quasi-Z-source cascade multilevel inverter-based photovoltaic power generation system. IEEE Trans Ind Electron 2015;62:5458–67. http://dx.doi.org/10.1109/TIE.2015.2407853.

[75] Liang W, Abu-Rub H, Liu Y, Ge B. State-of-charge balancing control for battery energy stored quasi-Z source cascaded multilevel inverter based photovoltaic power system. In: Proceedings of the 2015 IEEE energy convers congr expo (ECCE 2015); 2015. p. 8–13. http://dx.doi.org/10.1109/ECCE.2015.7309662.

[76] Xiao B, Hang L, Mei J, Riley C, Tolbert LM, Ozpineci B. Modular cascaded H-bridge multilevel PV inverter with distributed MPPT for grid-connected applications. IEEE Trans Ind Appl 2015;51:1722–31. http://dx.doi.org/10.1109/TIA.2014.2354396.

[77] Zhu H, Zhang D, Athab HS, Wu B, Gu YPV. isolated three-port converter and energy-balancing control method for PV-battery power supply applications. IEEE Trans Ind Electron 2015;62:3595–606. http://dx.doi.org/10.1109/TIE.2014.2378752.

[78] Benavides ND, Esram T, Chapman PL Ripple correlation control of a multiple-input dc-dc converter. In: Proceedings of the IEEE annu power electron spec Conf (PESC Rec 2005); 2005. p. 160–4. http://dx.doi.org/10.1109/PESC.2005.1581618.

[79] Benavides ND, Chapman PL. Power budgeting of a multiple-input buck-boost converter. IEEE Trans Power Electron 2005;20:1303–9. http://dx.doi.org/10.1109/TPEL.2005.857531.

[80] Debnath D, Chatterjee K. Two-stage solar photovoltaic-based stand-alone scheme having battery as energy storage element for rural deployment. IEEE Trans Ind Electron 2015;62:4148–57. http://dx.doi.org/10.1109/TIE.2014.2379584.

[81] Lu DDC, Agelidis VG. Photovoltaic-battery-powered DC bus system for common portable electronic devices. IEEE Trans Power Electron 2009;24:849–55. http://dx.doi.org/10.1109/TPEL.2008.2011131.

[82] Uoya M, Koizumi H. A calculation method of photovoltaic array's operating point for MPPT evaluation based on one-dimensional Newton-Raphson method. IEEE Trans Ind Appl 2015;51:567–75. http://dx.doi.org/10.1109/TIA.2014.2326083.

[83] Peter PK, Agarwal V. On the input resistance of a reconfigurable switched capacitor DC-DC converter-based maximum power point tracker of a photovoltaic source. IEEE Trans Power Electron 2012;27:4880–93. http://dx.doi.org/10.1109/TPEL.2012.2192452.

[84] Jiang S, Cao D, Li Y, Peng FZ. Grid-connected boost-half-bridge photovoltaic microinverter system using repetitive current control and maximum power point tracking. IEEE Trans Power Electron 2012;27:4711–22. http://dx.doi.org/10.1109/TPEL.2012.2183389.

[85] Wu TF, Kuo CL, Sun KH, Chen YK, Chang YR, Lee Y Der. Integration and operation of a single-phase bidirectional inverter with two buck/boost MPPTs for DC-distribution applications. IEEE Trans Power Electron 2013;28:5098–106. http://dx.doi.org/10.1109/TPEL.2013.2245681.

[86] Safari A, Mekhilef S. Simulation and hardware implementation of incremental conductance MPPT with direct control method using cuk converter. IEEE Trans Ind Electron 2011;58:1154–61. http://dx.doi.org/10.1109/TIE.2010.2048834.

[87] Mamarelis E, Petrone G, Spagnuolo G. Design of a sliding-mode-controlled SEPIC for PV MPPT applications. IEEE Trans Ind Electron 2014;61:3387–98. http://dx.doi.org/10.1109/TIE.2013.2279361.

[88] Lee JH, Park JH, Jeon JH. Series-connected forward-flyback converter for high step-up power conversion. IEEE Trans Power Electron 2011;26:3629–41. http://dx.doi.org/10.1109/TPEL.2011.2162747.

[89] Malathy S, Ramaprabha R. Comprehensive analysis on the role of array size and configuration on energy yield of photovoltaic systems under shaded conditions. Renew Sustain Energy Rev 2015;49:672–9. http://dx.doi.org/10.1016/j.rser.2015.04.165.

[90] ShamsEl-Dein MZ, Kazerani Mehrdad SMM. Optimal photovoltaic array reconfiguration to reduce partial shading losses. IEEE Trans Sustain Energy 2013;4:145–53.