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GMPPT by using PSO based on Lévy flight for photovoltaic system under partial shading conditions

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Rambabu Motamarri[1] ✉, Bhookya Nagu[1]
[1]Department of Electrical Engineering, National Institute of Technology Warangal, Hanamkonda, Telangana, India
✉ *E-mail: ramu77motamarri@student.nitw.ac.in*

Abstract: The photovoltaic (PV) system contemplated in the study displays multiple peaks on power–voltage (*P*–*V*) curve under partial shading condition (PSC) results in a complicated maximum power point tracking (MPPT) process. Conventional MPPT algorithms work in an effective manner under uniform irradiance conditions. However, these algorithms are unable to track the global peak effectively under different irradiance conditions. In this study, a velocity of particle swarm optimisation-based Levy flight (VPSO-LF) for Global MPPT of PV system under PSCs is proposed. For the changes in irradiance, when verified with VPSO-LF, tracking time and a number of iterations are fewer to reach the global peak of PV array. It also minimises the number of tuning parameters of the velocity of particle swarm optimisation (PSO). The proposed technique is simulated in MATLAB/SIMULINK as well as experimentally validated. It is observed that the results obtained using VPSO-LF is superior to conventional PSO and hill-climbing algorithm under different patterns of PV array.

1 Introduction

Compared to several non-conventional energy sources, photovoltaic (PV) system offers several advantages such as easy maintenance, inexpensive cost of setting up, flexibility with regard to location as it can be set up on the building, with sunlight being a perennial source of energy. For the conversion of power, many topologies have been considered based on PV system, such as SEPIC converter and boost converter that are used in industrial applications and power sector as in rural electrification (lightening system based on PV-power generation), PV power to DC microgrids, charging station for electrical vehicle and charging of battery [1]. The generation of power from a PV system depends on irradiance and temperature and its *P*–*V* curve has a single peak called maximum power point tracking (MPPT). When the solar irradiance changes, maximum power point (MPP) also changes. There are many algorithms available for MPPT which comprise Perturb and Observe (P&O), hill climbing (HC), incremental conductance (INC) etc.

PV arrays [2] consist of a number of modules and each module is composed of series–parallel connection of solar cells. In such cases, PV array receives different solar irradiance on each module because of weather, shade from trees and vegetation, tall buildings and neighbouring objects. During partial shading condition (PSC), hot spots are created due to the modules consuming power instead of going to load. To avoid these bypass diodes are connected across the PV modules. Under PSC, the voltage across each module is different for series-connected modules and parallel connected modules current flowing through them are also different. This makes the PV array show multiple peaks on the *P*–*V* curve. From multiple peaks, the highest peak identified is called global maximum power point (GMPP) while the remaining peaks are called local maximum power points (LMPPs). These local and global MPPs depend on changing irradiance condition and PV array pattern. Conventional MPPT algorithms are not able to track GMPP on multiple peaks on the *P*–*V* curve; they are suitable to track only a single peak on the *P*–*V* curve. This problem can be overcome by employing suitable optimisation techniques under PSC. The conventional methods such as P&O [3], HC [4] and IC [5] are best suited for single peak curves to get MPPT and also its improved methods [6–10]. The main drawbacks of conventional methods are loss of power during steady-state and also poor performance. Steep change of irradiance happens due to step size. Nguyen and Low [11], Patel and Agarwal [12], Alireza *et al.* [13] have proposed various algorithms for locating GMPP but the initial values are dependent on V_{OC}. Furthermore, even if the global MPP is found, Jubaer and Zainal [14] report that $0.8V_{OC}$, the method is not always valid, especially in long PV pattern. The algorithm may track the local peak instead of a global peak on the *P*–*V* curve. Optimisation algorithms under PSC such as PSO [15] were implemented with higher efficiency, taking 30 iterations with three tuning parameters such as weight factor, two-parameter cognitive factors. DPSO [16] limits the velocity, remove the random number, improve the tracking capability of conventional PSO with only one weight factor, MPSO [17], velocity-based PSO [18] discards the tuning of weight of PSO, while also showings the nature of deterministic behaviour and adaptive and tuning of cognitive factors with the current position. Other algorithms such as ant colony optimisation (ACO) [19], LPSO [20] and ICS [21] tracked global peak quickly, hybrid APO & PSO [22] track GMPP fast. Firefly algorithm (FA) [23], artificial bee colony (ABC) [24], grey wolf optimisation (GWO) [25], flower pollination algorithm (FPA) [26], recent works to increase the tracking speed OD-PSO [27], hybrid ELPSO-P&O [28], ANN GMPP [29] and FI-GMPP [30] are used for tracking GMPP under multiple peaks on the *P*–*V* curve.

This paper proposes identifying velocity of PSO based on Lévy flight (LF) for tracking GMPP under PSCs. In conventional PSO, the velocity is updated randomly and with more tuning parameters, and slow search efficiency. Due to this, convergence time and iterations increase before reaching a steady-state position and the algorithms also possess more tracking oscillations. However, in the algorithm, the step size is updated by LF instead of determining the velocity randomly in order to increase search efficiency and reduce the convergence time of GMPP using fewer iterations with low tracking and steady-state oscillations. The rest of the paper is organised into various sections with a discussion of PV system modelling, GMPPT methods, simulation results, experimental results, comparative study, followed by conclusions.

2 PV system modelling

For modelling and simulating PV system used a single-diode PV cell is shown in Fig. 1. It is implemented in MATLAB/SIMULINK environment based on the steps given in [31].

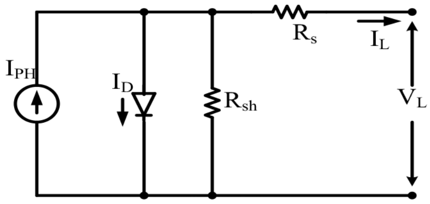


Fig. 1 *Equivalent circuit of single-diode PV cell*

Table 1 PV module parameters

P_{max}	V_{OC}	I_{SC}	V_{max}	I_{max}
60 W	21 V	3.8 A	17.1 V	3.5 A

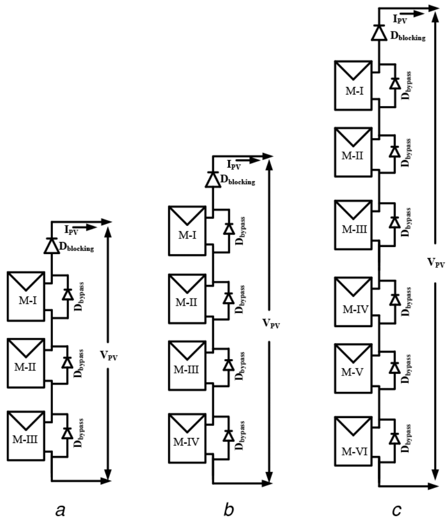


Fig. 2 *Series configurations of PV array under partial shading*
(a) Three PV modules in series (3S), ***(b)*** Four PV modules in series (4S), ***(c)*** Six PV modules in series (6S)

The basic equations concerned with the modelling of the PV system are described below. The specifications of the PV module are given in Table 1.

By applying nodal analysis to the circuit shown in Fig. 1, the output current of the PV cell is expressed as

$$I_L = I_{PH} - I_D - \frac{V_L + I_L R_S}{R_{sh}} \tag{1}$$

In general, a combination of series and parallel cells forms a PV module. The current given by the PV module is

$$I_m = N_P I_{PH} - N_P I_D - \frac{V_m + I_m R_{s\_m}}{R_{sh\_m}} \tag{2}$$

where current flow through the Shockley diode equation is

$$I_D = I_{sat}\left[e^{q(V_L + I_L R_S)/akTN_s} - 1\right] \tag{3}$$

The saturation current of diode mainly depends on temperature and is modelled as

$$I_{sat} = I_{sat\_n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \tag{4}$$

$$I_{sat\_n} = \frac{I_{sc\_n}}{\exp(V_{oc\_n}/AV_{t\_n}) - 1} \tag{5}$$

The photon energy I_{PH} of PV cell is the current generated by solar irradiance falling on the PV cell. This varies in proportion to the change of solar irradiance and also depends on temperature. It is modelled thus

$$I_{PH} = (I_{PH_n} + K_i \Delta T)\frac{G}{G_n}, \tag{6}$$

where $\Delta T = T - T_n$ is the proposed algorithm can be verified with three different PV array configurations. The three PV arrays are formed by connecting three PV modules in series (3S), four PV modules in series (4S) and six PV modules in series (6S) as shown in Fig. 2 and the *P*–*V* characteristics are shown in Fig. 3 and its module irradiance level is presented in Table 2.

3 GMPPT methods

3.1 GMPPT through HC algorithm

HC is a conventional MPPT and most commonly adopted method because of its simplicity and low cost. The algorithm provides a direct duty cycle [3] to the boost converter. Based on this duty, maximum power can be observed at the output of the PV array. So, from the literature, the conventional methods are [3–10, 12]. The duty cycle $d(k)$ of HC is changed by perturbation size 'θ'. The size is dependent on the change of maximum power by the following equations:

$$d_{new} = d_{old} + \theta \quad \text{if } P > P_{old} \tag{7}$$

$$d_{new} = d_{old} - \theta \quad \text{if } P < P_{old} \tag{8}$$

An advantage of this algorithm is that there is no requirement of any P or PI controller for pulse generation to control the duty ratio of the boost converter.

3.2 GMPPT through PSO algorithm

Eberhart and Kennedy proposed a PSO algorithm [32] in 1995. The PSO algorithm is designed for a control purpose, while MPPT was first proposed for [33]. PSO is a population-based evolutionary algorithm, modelled on the behaviour of bird flocks. The PSO algorithm maintains a swarm of individuals, i.e. particles, where each particle is appointed to act as a solution of a candidate. These particles follow a set of behaviour to emulate the success of neighbouring particles and their own to achieve success. The particle position is affected by the best particle in the neighbourhood, i.e. P_{besti}. The best particle is created by all the particles in the whole population denoted as G_{best}. The particle position X_i is updated as

$$X_i^{k+1} = X_i^k + \theta_i^{k+1} \tag{9}$$

where the component of velocity θ_i represents the perturb size. The velocity is computed as follows:

$$\theta_i^{k+1} = w\theta_i^k + C_1 R_1\left[P_{besti} - X_i^K\right] + C_2 R_2\left[G_{best} - X_i^k\right] \tag{10}$$

where w is the inertia weight, C_1 and C_2 are the acceleration coefficients, R_1 and $R_2 \in U(0, 1)$, P_{besti} is the personal best position of a particle i, and G_{best} is the optimum position of the particle in the whole population.

If a position is represented as a duty cycle and the step size is velocity, then (11) can be represented as:

$$d_i^{k+1} = d_i^k + \theta_i^{k+1} \tag{11}$$

By comparing (7) and (11) both HC [3] and PSO [15] are equivalent.

3.3 Lévy flight

There are two steps for the production of random numbers with LF [34–38], i.e. the selection of random direction and the production of steps which obey the chosen Lévy distribution. Random walks are taken from Lévy stable distribution. The simple formula for power-law $(s) \sim |s|^{-1-\beta}$, where $0 < \beta < 2$ is an index.

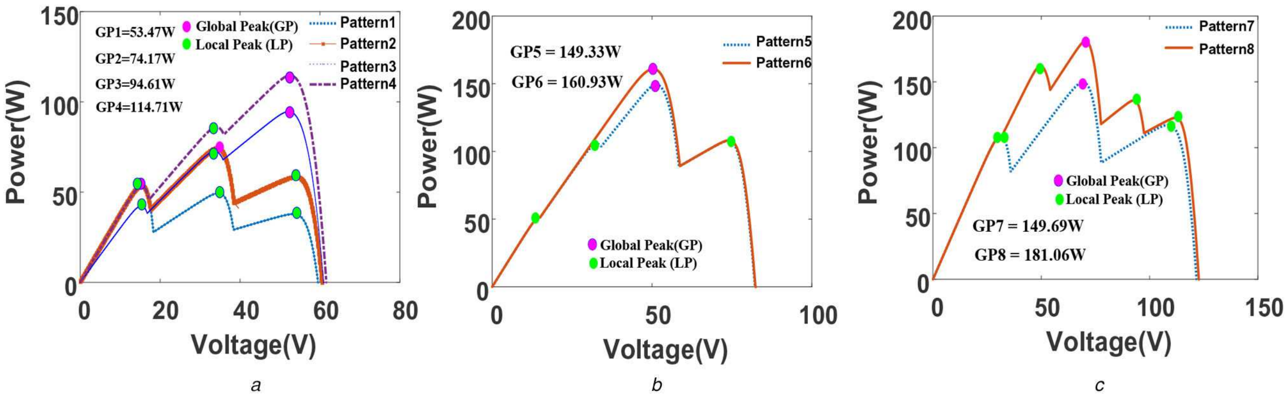


Fig. 3 *P–V characteristics of PV array*
(a) 3S, ***(b)*** 4S, ***(c)*** 6S

Table 2 Irradiance (W/m^2) of each module in various patterns

Module (M)	Pattern-1	Pattern-2	Pattern-3	Pattern-4	Pattern-5	Pattern-6	Pattern-7	Pattern-8
M-I	1000	1000	800	1000	1000	1000	1000	1000
M-II	400	600	600	700	900	900	1000	1000
M-III	200	300	500	600	800	900	600	900
M-IV	—	—	—	—	400	400	600	700
M-V	—	—	—	—	—	—	300	400
M-VI	—	—	—	—	—	—	300	300

*Definition 1: : D*istribution of Lévy can be specified as

$$L(s,\gamma,\mu) = \left\{\sqrt{\frac{\gamma}{2\pi}}\ \exp\left[-\frac{\gamma}{2(s-\mu)}\right]\frac{1}{(s-\mu)^{3/2}}\right\},$$
$$\text{if } 0 < \mu < s < \infty \quad (12)$$
$$\text{or}$$
$$= 0, \quad \text{if } s \le 0$$

where μ is a parameter location, $\gamma > 0$ is parameter scale.

Definition 2: Lévy distribution can be specified in the form of a Fourier transform

$$F(k) = \exp\left[-\alpha|k|^{\beta}\right],\ 0 < \beta \le 2 \quad (13)$$

where α is a parameter among $[-1, 1]$ interval and recognised as skewness or scale factor. Stability index between $\beta \in (0,\ 2)$is considered as Lévy index.

For a random walk, step distance S can be accounted for by Mantegna's algorithm as

$$S = \alpha \oplus \text{Lévy}(\lambda),$$
$$\alpha = \alpha_0(P_{\text{best}} - x_i), \quad (14)$$

where α_0 is the initial step change.

A modified scheme of Lévy distribution is

$$\text{Lévy walk}(x_i^t) = \alpha_o\,(p_{\text{best}} - x_i) \oplus \text{Levy}(\lambda)$$
$$\simeq K \times \left(\frac{u}{(|v|)^{1/\beta}}\right)(p_{\text{best}} - x_i) \quad (15)$$

When $\beta = 1.5$, the designer has to choose the coefficient of Lévy by multiplying factor K. Where u and $v$are obtained from a normal distribution, i.e. $u \sim N(0, \sigma_u^2)v \sim N(0, \sigma_v^2)$ If Γ denotes the integral gamma function, then variables σ_u and σ_v are defined as

$$\text{where } \sigma_u = \left(\frac{\Gamma(1+\beta)\times\sin(\pi\times\beta/2)}{\Gamma((1+\beta)/2)\times\beta\times(2)^{((\beta-1)/2)}}\right)^{1/\beta} \text{ and } \sigma_v = 1 \quad (16)$$

3.4 GMPPT through proposed VPSO-LF algorithm

From the literature, it can be observed that the PSO algorithm is employed to keep from slow convergence and local MPPT. Different algorithms related to an improved PSO are also proposed in [15, 17, 18] with updated step size in a different form. However, in the proposed method, velocity (step size) can be updated by LF, which is the same as standard PSO. Initial duty cycles (particles) are randomly taken within a range, and fitness (power) value is evaluated from each particle (duty cycle).

Particle P_{best} and global G_{best} are also obtained, after which the position and velocity are updated as per standard PSO [15] given in (9) and (10), respectively, with a probability of <0.25. If the condition provided in the proposed algorithm has a value of <0.25, the position and velocity are updated according to (9) and (10), if its value is >0.25 then update velocity and position are updated according to (17) and (18). By updating the velocity with LF, the particle takes a small step and searches for P_{best} and G_{best}, thereby intensifying the variation of the swarm and facilitating the algorithm to accomplish global exploitation search throughout the space. In the proposed algorithm, the parameter β can play a great job in distribution and the ideal value is considered to be 1.5.

The VPSO-LF algorithm presents the velocity of PSO, which is continuously updated with and without LF based on the condition shown in the flowchart of the proposed algorithm. The search area of LF with a small step size is compared to normal velocity for exploitation process; the step size is updated with a long jump from one area to another area of searching for exploration process. Due to this, the tracking speed is high and takes fewer iterations to track GMPP.

The proposed algorithm is shown in Fig. 4. The new particle position is updated as shown in (18) from (17)

$$\theta_i^{t+1} = w \times Levy_{\text{walk}}(x_i^t) + C_1R_1(pbest_i - x_i^t) + C_2R_2(gbest - x_i^t) \quad (17)$$

$$x_i^{t+1} = x_i^t + \theta_i^{t+1} \quad (18)$$

The change of shading pattern is represented by the following equation:

$$\frac{|P_{n+1} - P_n|}{P_n} \ge \delta \quad (19)$$

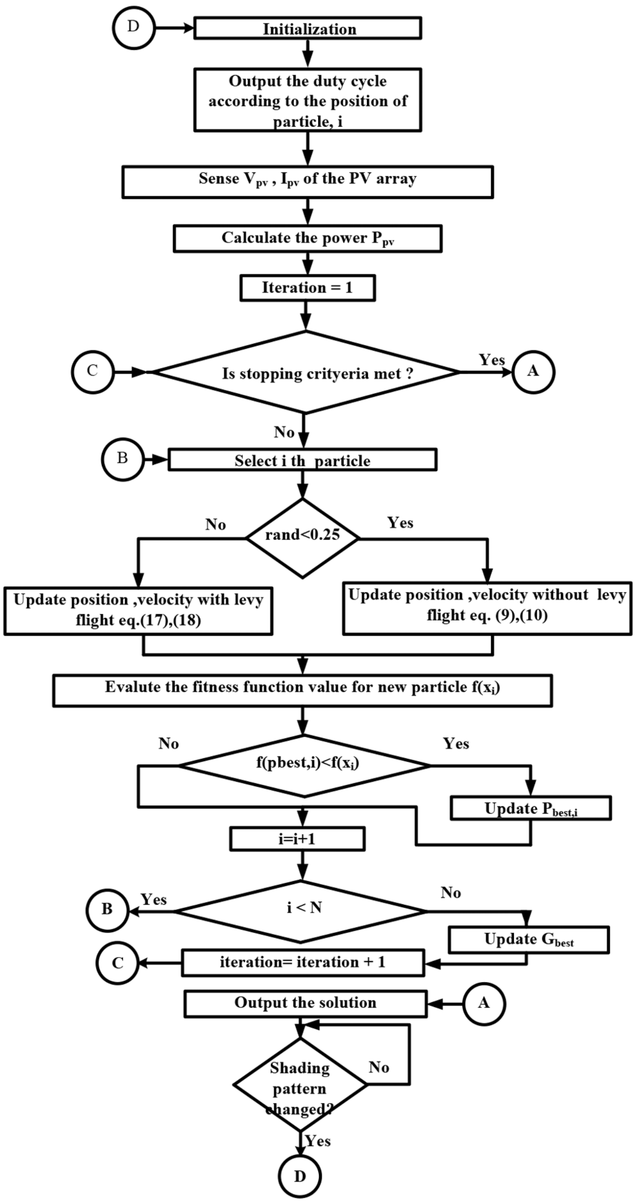


Fig. 4 *Proposed VPSO-LF algorithm*

The term P_n is the present and P_{n+1} is the next power output of the PV system, δ is the percentage change in power 2% according to [39].

4 Simulation results

4.1 Simulation results of PV array under PSC

The schematic diagram of the boost converter is shown in Fig. 5. The simulation studies are performed by using the proposed VPSO-LF algorithm for GMPPT in MATLAB/SIMULINK for eight possible cases of PSCs. In each PSC case, PV modules are connected in a series called the pattern. These patterns are one left most peak, one middle peak and two rightmost peaks of PV array of 3S configuration, second and third from the left side of *P–V* curve of 4S configuration and two middle peaks of *P–V* curve of 6S configuration. Initialisation particles of VPSO-LF and PSO called duty cycle of boost converter taken are three $x_1 = 0.2$, $x_2 = 0.3$ and $x_3 = 0.7$, other parameters of algorithms and boost converter are shown in Table 3.

The Simulink model of the proposed system of PV array connected to a boost converter is shown in Fig. 6*a* and the PV array in Simulink with blocking and bypass diode are shown in Fig. 6*b*. The proposed VPSO-LF algorithm is implemented using s-function in MATLAB/SIMULINK as per flowchart shown in Fig. 4. In order to validate the results of the proposed algorithm, it is compared with HC and PSO algorithms. The results are verified with eight patterns of PV array under PSC.

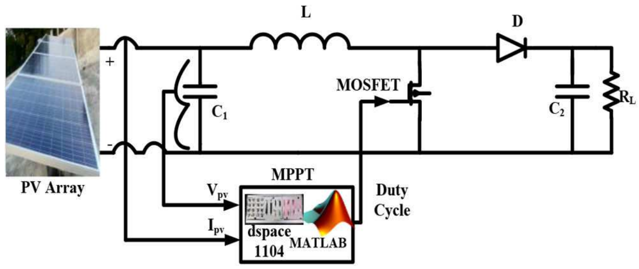


Fig. 5 *Schematic diagram of the boost converter*

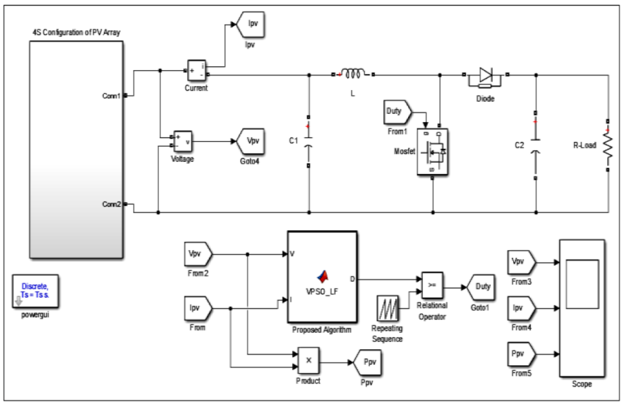
4.2 Simulation results of 3S configuration

Pattern-1: the first pattern of PV array consists of three modules connected in series, as shown in Fig. 2*a*. Module-I takes irradiance of 1000 W/m^2, Module-II takes 400 W/m^2 and Module-III uses 200 W/m^2. Due to three irradiances, three different peaks are available as characteristics of the *P–V* curve are shown in Fig. 3*a*. In this, the leftmost peak is the highest peak called global peak (GP) and its value is 53.47 W; the remaining peaks which are middle and rightmost peaks are local peaks (LPs). So this pattern-1 is applied as a PV source to the input of boost converter, and the results are observed in simulation with HC, PSO and the proposed VPSO-LF algorithm; the corresponding PV power, PV voltage and PV current waveforms, as shown in Fig. 7. The power obtained by the HC algorithm is 52.05 W and its tracking time is 0.3 s, but there is a loss of power during tracking and steady-state oscillations are also observed. The power obtained by a PSO algorithm is 53.39 W with a tracking time of 2.16 s and 15 iterations are required to reach the global peak, but there are more oscillations during tracking and less steady-state oscillations compared to the HC method. By using the proposed VPSO-LF algorithm, the power obtained is 53.39 W with a tracking time of 0.3 s and the required iterations are 2 to reach the global peak of pattern-1. In the proposed method, the power oscillation during tracking and steady-state are less compared to HC and PSO methods and the method also takes less tracking time. From pattern-1 results, it is observed that the proposed VPSO-LF algorithm is superior to HC and PSO algorithms. The VPSO-LF algorithm searches the feasible search area in small step increments at the initial stage. This improves the exploitation capability of the PSO algorithm by changing the velocity in small the increments. In later stages, LF adopts large step size, which improves the exploration ability of the PSO algorithm by changing the velocity in large increments. The corresponding searching of velocity particle values of VPSO-LF and PSO with respect to the number of iterations according to [18] are shown in Fig. 8. Similarly, the system is going to verify with 3S configuration of different shading patterns, already considered as the leftmost peak as a global peak while going to test with middle and rightmost peaks as a global peak in the next patterns of the PV array. The 3S configuration of four patterns is presented in Table 4.

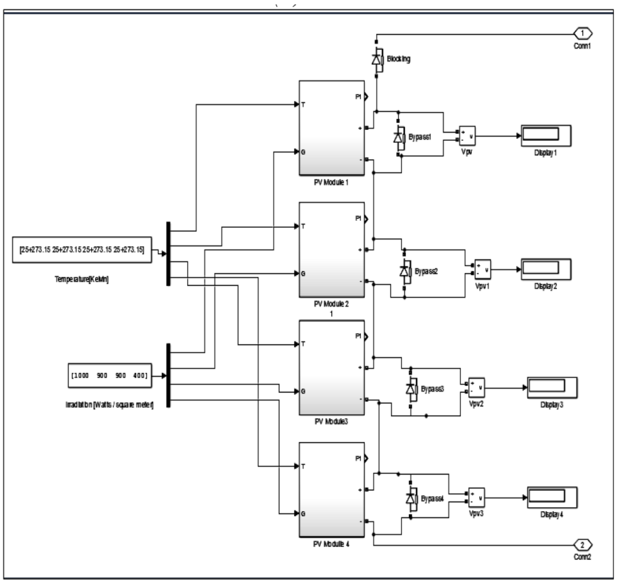
Pattern-2: The shading pattern-2 is considered as a middle peak, and the corresponding irradiance values are also shown in Table 2. In pattern-2, three-module irradiances are different while the three peaks are available in the *P–V* curve, as shown in Fig. 3*a* and the global peak is the middle peak, while the remaining peaks (leftmost and rightmost) are local peaks. The global peak value power is 74.17 W. The PV power extracted by the HC algorithm is 71.45 W, also shown as PV voltage and current in Fig. 9. Based on the observation from HC, the tracking time is 0.30 s but steady-state oscillations are more due to step size. PSO algorithm applied to the PV system and the related waveforms are shown in Fig. 9. The maximum power obtained by the PSO algorithm is 72.67 W, and the time taken to reach the global peak is 2.98 s along with 20 iterations. The tracking time and iterations needed are more to reach global peak due to three tuning parameters. The proposed VPSO-LF is applied to PV system and the time is taken for tracking is 0.71 s to reach a global peak in five iterations, while the

Table 3 Parameters of algorithms and boost converter details

Particulars	Specifications
VPSO - LF	$w = 0.4,\ C_1 = 1.6,\ C_2 = 1.8,\ \beta = 1.5,\ K = 0.01,$ population size = 3
PSO	$C_{1,\min} = 1,\ C_{1,\max} = 2,\ C_{2,\min} = 1,\ C_{2,\max} = 2,$ $w_{\min} = 0.1, w_{\max} = 1$, population size = 3
HC	$D_{\text{initial}} = 0.7, \theta = 0.035$
boost coverter	$L = 1.928\,\text{mH},\ C_1 = C_2 = 100\,\mu\text{F},$ $F_s = 10\,\text{kHz}$, diode – MUR860, MOSFET – IRFP460, 240 V 20 A variable resistive load
sampling period (T_s)	for simulation $T_s = 50\,\text{ms}$, for experimental $T_s = 200\,\text{ms}$



a



b

Fig. 6 *Simulink model of the proposed system*
(a) Implementation of the proposed algorithm, ***(b)***Series connection of PV modules

maximum power is achieved by the proposed VPSO-LF algorithm of 73.95 W; voltage and current waveforms are shown in Fig. 9. From these three algorithms, VPSO-LF yields better results when compared to PSO and HC.

Pattern-3: The *P–V* curve of shading pattern-3 also has three peaks in which the third peak is the global peak, the leftmost and middle are local peaks. The maximum power delivered by pattern-3 is 94.61 W. The conventional HC algorithm is applied to pattern-3, with tracking time and GMPP value being 0.30 s and 90.70 W, respectively. The waveforms of pattern-3 of the conventional HC algorithm are shown in Fig. 10. By observing power waveform, the tracking time is less, but has steady-state

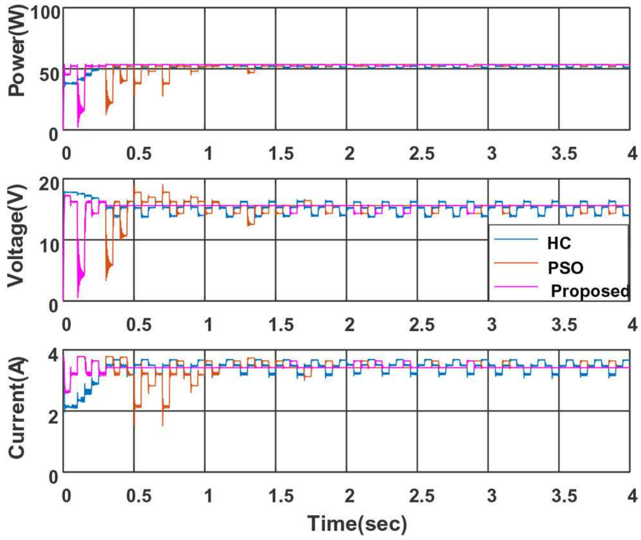


Fig. 7 *Simulation results of pattern-1*

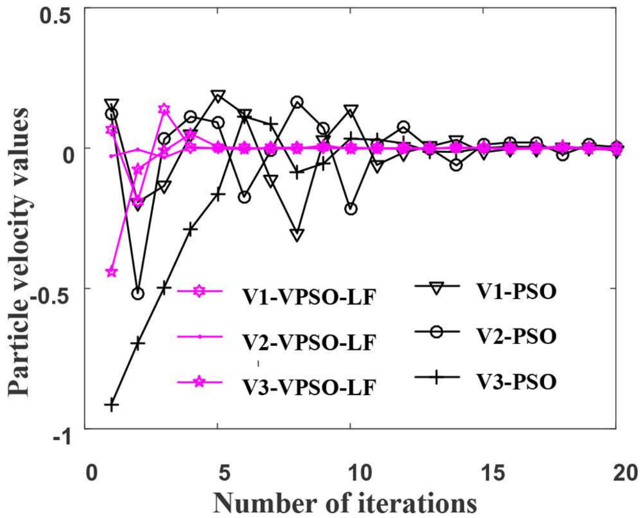


Fig. 8 *Comparisons of VPSO-LF and PSO particle velocity values with the number of iterations*

oscillations similar to above pattern-1 and pattern-2. PSO algorithm is applied to pattern-3, with tracking time of 3.52 s to get GMPP with 24 iterations and global peak power of 94.11 W. The power is achieved, but the tracking time and iterations are more to get global peak power. By using the proposed VPSO-LF algorithm, the tracking time is 0.75 s with 5 iterations and a GMPP of 94.58 W, but the proposed algorithm overcomes limitations of PSO and conventional HC algorithm, takes less tracking time and fewer iterations for the location of the global peak; the corresponding results are shown in Fig. 10.

Pattern-4: Pattern-4 *P–V* curves are similar to pattern-3. The global peak power of this pattern is 114.71 W. Conventional HC algorithm takes 0.35 s to track global peak is 0.35 s and the maximum power 109.90 W. The tracking time to reach global power using PSO is 3.50 s and the maximum power is 114.70 W with 24 iterations. The proposed VPSO-LF method tracking time is 0.23 s and the global peak power is 114.70 W within 2 iterations. So the VPSO-LF has better tacking time and fewer iterations compared to PSO and HC algorithms; corresponding results are shown in Fig. 11.

Dynamics of pattern-2 to pattern-4: Whenever there is a change in one pattern to other patterns of PV array under PSC at a particular time, the algorithm has to be reinitialised to track new GMPP. VPSO-LF algorithm, PSO algorithm and conventional HC algorithms are verified with a change of from pattern-2 to pattern-4 at 4 s according to [30]. The results prove (change of power from 74.17 to 114.71 W) that the dynamic case is also working in perfect in manner. The waveforms are shown in Fig. 12, which present the

Table 4 Performance analysis of the proposed VPSO-LF along with HC and PSO algorithms for PV array of 3S configurations

Technique to extract maximum power	Rated power, W	Maximum power extracted from PV, W	Maximum voltage extracted from PV, V	Maximum current extracted from PV, A	Tracking time, s	Iterations required to reach GMPP	Maximum efficiency extracted from PV, %
proposed	53.47pattern-1	53.39	15.61	3.42	0.30	2	99.85
PSO		53.39	15.61	3.42	2.16	15	99.85
HC		52.05	15.31	3.40	0.30	—	99.35
proposed	74.17pattern-2	73.95	34.72	2.13	0.71	5	99.70
PSO		72.67	34.12	2.13	2.98	20	97.98
HC		71.45	33.96	2.10	0.30	—	96.33
proposed	94.61pattern-3	94.58	51.40	1.84	0.75	5	99.97
PSO		94.11	51.15	1.84	3.52	24	99.47
HC		90.70	52.43	1.73	0.30	—	95.81
proposed	114.71pattern-4	114.70	52.63	2.18	0.23	2	99.99
PSO		114.70	52.63	2.18	3.50	24	99.99
HC		109.90	50.87	2.16	0.35	—	95.81

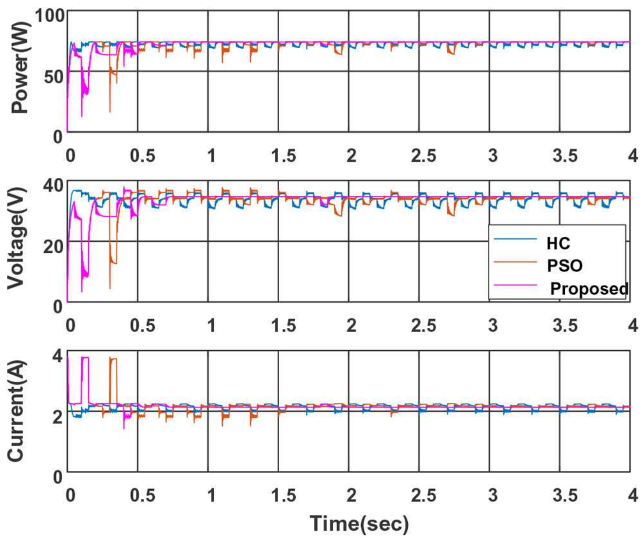


Fig. 9 *Simulation results of pattern-2*

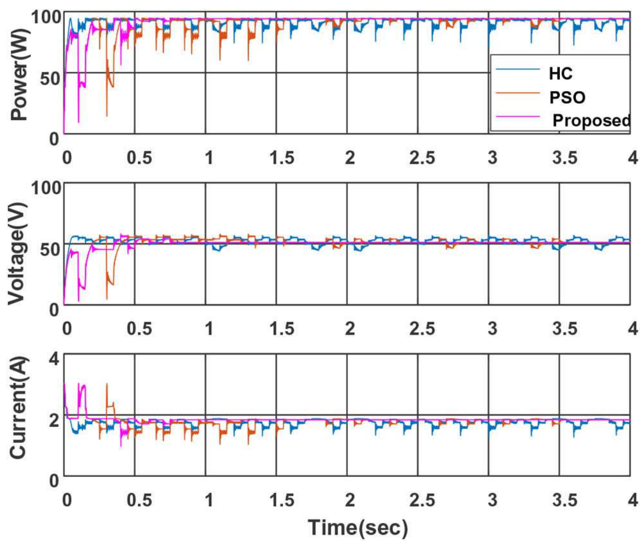


Fig. 10 *Simulation results of pattern-3*

superior performance of VPSO-LF when compared with PSO algorithm and conventional HC algorithm.

4.3 Simulation results of 4S configuration

In the previous cases, the proposed algorithm was tested with three modules in series; in each case, three irradiances were different and

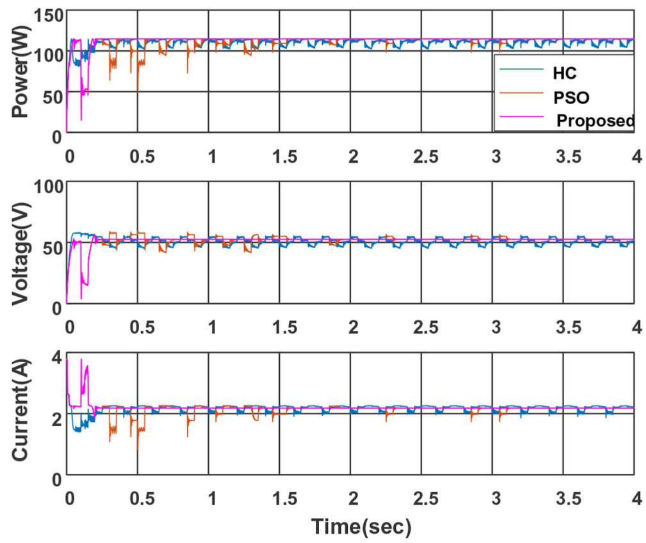


Fig. 11 *Simulation results of pattern-4*

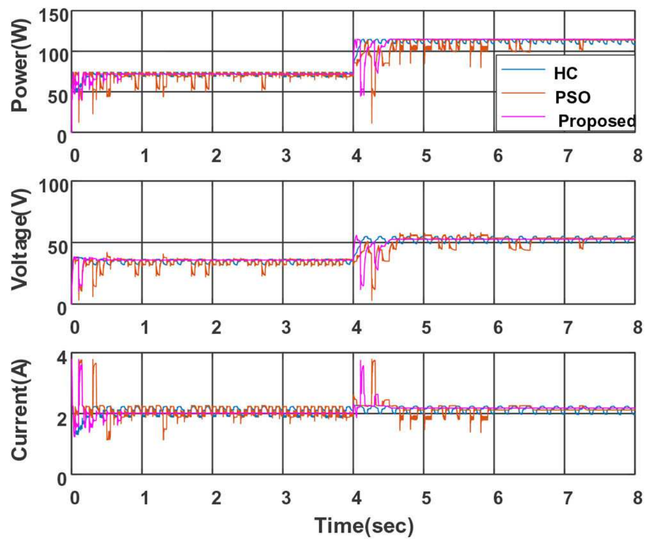


Fig. 12 *Dynamics results of HC, PSO and proposed VPSO-LF algorithm of pattern-2 to pattern-4*

there were different global peaks. Now four modules are connected in series to form a PV array as shown in Fig. 2*b*; four different irradiances are considered to form pattern-5 and three different irradiances to form pattern-6, its module values are shown in Table 2, the proposed algorithm was tested with four peaks and three peaks of 4S configuration, its *P–V* curves shown in Fig. 3*b*.

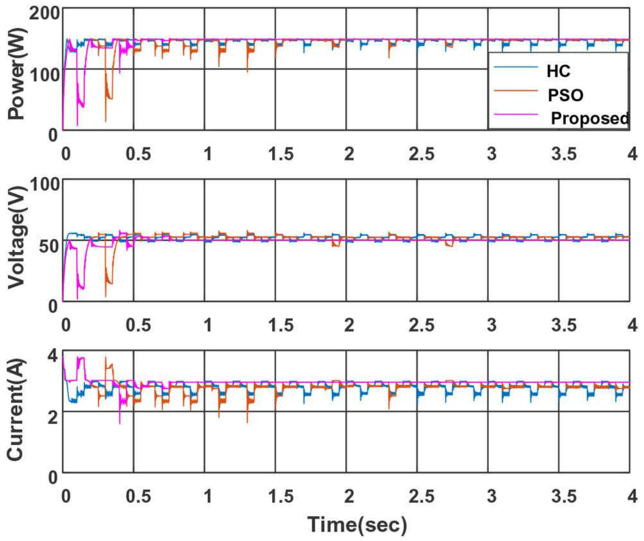


Fig. 13 *Simulation results of pattern-5*

Table 5 Performance analysis of the proposed and existing algorithms for PV arrays 4S and 6S configurations

Technique to extract maximum power	Rated power, W	Maximum power extracted from PV, W	Maximum voltage extracted from PV, V	Maximum current extracted from PV, A	Tracking time, s	Iterations required to reach GMPP	Maximum efficiency extracted from PV, %
proposed	149.33pattern-5	148.59	50.37	2.95	0.75	5	99.50
PSO		147.83	51.69	2.86	2.78	19	98.99
HC		143.98	51.24	2.81	0.20	—	96.42
proposed	160.93pattern-6	159.44	48.55	3.28	0.23	2	99.07
PSO		159.50	48.57	3.28	2.57	17	99.11
HC		157.19	50.22	3.13	0.20	—	97.68
proposed	149.69pattern-7	149.48	68.57	2.18	0.87	4	99.86
PSO		149.30	68.49	2.18	3.13	14	99.74
HC		143.06	66.54	2.15	0.40	—	95.57
proposed	181.06pattern-8	180.89	69.87	2.58	0.52	2	99.91
PSO		180.89	69.87	2.58	3.57	15	99.91
HC		173.54	69.03	2.51	0.30	—	95.85

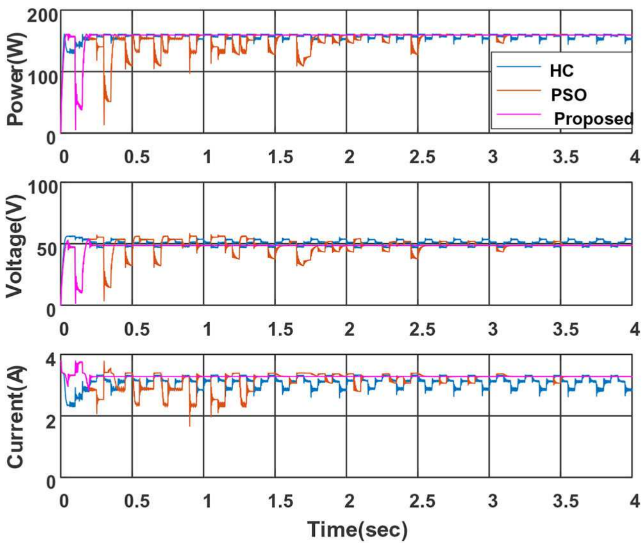


Fig. 14 *Simulation results of pattern-6*

Pattern-5: Pattern-5 irradiances of each module are M-I-1000 W/m^2, M-II-900 W/m^2, M-III-800 W/m^2 and M-IV-400 W/m^2. The four irradiances are different because of which are four peaks in the *P–V* curve of pattern-5; the respective *P–V* curve of pattern-5 is shown in Fig. 3*b*. In pattern-5, the global peak is third from the left of the *P–V* curve and its maximum power is 149.33 W. So the PV system's complexity has increased compared to the previous configuration. The proposed system was tested with pattern-5 and the results of the proposed method along with two existing methods are shown in Fig. 13. HC method takes 0.2 s to reach the global peak with a power of 143.98 W, but it has problems of steady-state oscillations. The PSO method tracks global power of 147.83 W with a tracking time of 2.78 s and uses 19 iterations. The proposed takes 0.75 s to reach the power of 148.59 W along with 5 iterations. The proposed VPSO-LF algorithm can overcome the problem of PSO and HC algorithms. A detailed explanation of 4S configuration is shown in Table 5.

Pattern-6: In this, three different irradiances of PV array, M-I-1000 W/m^2, M-II and M-III of 900 W/m^2, M-IV-400 W/m^2 are considered. The global peak is in the middle, its maximum power being 160.93 W. Under simulation conditions, the HC tracking time is 0.2 s, the power use up is 157.19 W. PSO takes 2.57 s to reach the global point of 159.50 W with 17 iterations. The proposed VPSO algorithm takes only 2 iterations and 0.23 s to locate GP of 159.44 W. In pattern-6, VPSO-LF algorithm is best suited for GMMP tracking compared to HC and PSO. A comparative analysis of 4S configuration of pattern-5 and pattern-6 shown in Table 5. The tracking of PV power, voltage and current waveforms of pattern-6 are shown in Fig. 14.

4.4 Simulation results of 6S configuration

The number of modules of the PV array is increased to six to form a 6S configuration as shown in Fig. 2*c*, corresponding to values of irradiances under PSCs shown in Table 2. There are three different

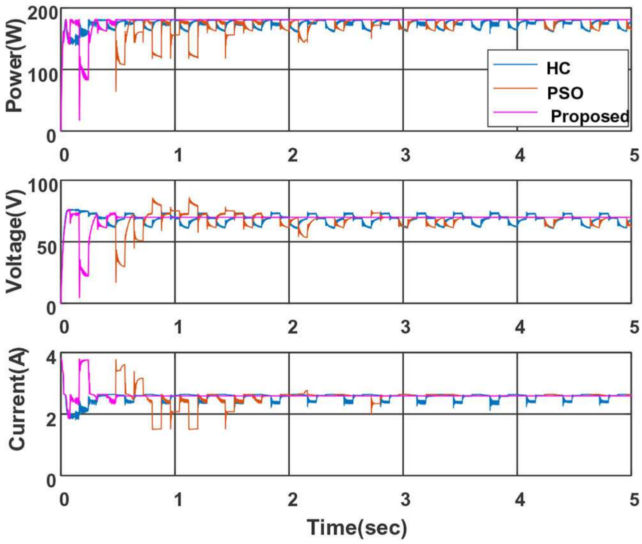


Fig. 15 *Simulation results of pattern-7*

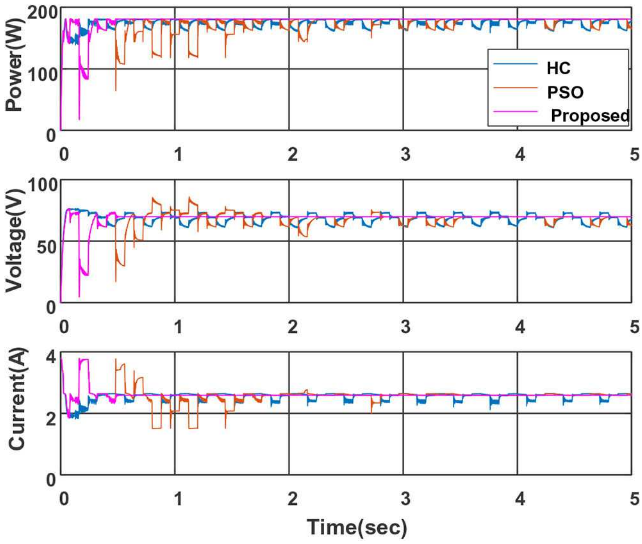


Fig. 16 *Simulation results of pattern-8*

irradiances considered for pattern-7 and five different irradiances for pattern-8; its *P–V* curves are shown in Fig. 3*c*. A detailed comparison of the results is shown in Table 5. Now PV array complexity increases compared to previous 3S and 4S configurations.

Pattern-7: In this pattern, the M-I and M-II receive irradiance of 1000 W/m^2, M-III and M-IV of 600 W/m^2, M-V and M-VI are 300 W/m^2. For three different irradiances, there will be three peaks in the *P–V* curve of pattern-7, as shown in Fig. 3*c*, in which the middle peak is the global peak, with a corresponding power of 149.69 W. The results of HC method take 0.4 s to locate GP of 143.06 W; steady-state oscillations are near GP. PSO algorithm finds GP with a tracking time of 3.13 s and takes 14 iterations consuming 149.30 W, but it has problems with regard to tracking time and oscillations due to velocity tuning with three parameters. The proposed VPSO-LF takes 0.87 s to locate GP of 149.48 W with 4 iterations. In this too, the proposed algorithm is superior to HC and PSO. The tracking power, voltage and current of pattern-7 of waveforms are shown in Fig. 15.

Pattern-8: In this pattern, there are five different irradiances which form pattern-8; there are five peaks available in the *P–V* curve of pattern-8 as shown in Fig. 3*c*. Its corresponding irradiances are 1000, 1000, 900, 700, 400 and 300 W/m^2.

The third peak is a global peak with a power of 181.06 W. In this case, the results obtained by HC are 173.54 W near GP with a time of 0.3 s. PSO algorithm locates GP with a time of 3.57 s and takes 15 iterations. The proposed VPSO-LF algorithm settles GP at

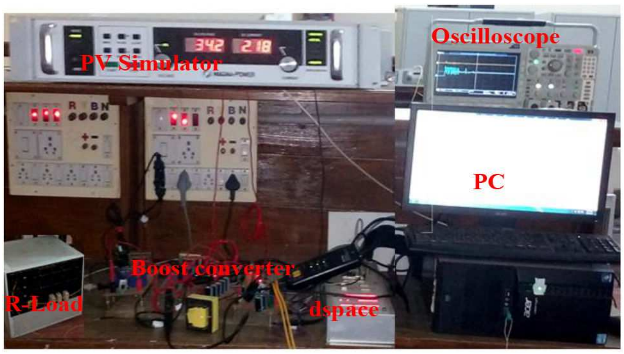


Fig. 17 *Experimental setup*

180.89 W with a tracking time of 0.52 s, taking 2 iterations. VPSO-LF has a dynamic response compared to HC and PSO algorithms. The tracking waveforms of pattern-8 are shown in Fig. 16.

5 Experimental results

A hardware-setup was developed comprising PV simulator followed by a boost converter to validate the performance of the proposed VPSO-LF algorithm, PSO algorithm and conventional HC algorithm. These algorithms are implemented with a MATLAB interface with dspace-1104 controller by the voltage sensor (LV25-p), and the current sensor (LA55-p) is input to the algorithms. The *P–V* characteristics are verified by using PV simulator (Magna power electronics XR600-9.9/415 + PPPE + HS). The experimental setup is shown in Fig. 17. The real-time parameters are the same as simulations as shown in Table 3. In order to verify the GMPP of multiple peaks on the *P–V* curve, three PV array configurations were considered with different irradiance conditions in each case, as shown in Fig. 2. The irradiance of each module in each pattern is shown in Table 2.

5.1 Results of 3S configuration

The advantages of the proposed VPSO-LF over PSO and HC algorithms is that, the number of iterations required to reach global MPP is minimum and tracking and steady-state oscillations are also fewer as was observed in simulation results. The proposed algorithm was implemented in hardware to verify simulation results and a screenshot of GMPP on the *P–V* curve was also taken to validate the efficiency in real-time. In Table 6 the performance analysis of 3S configuration of four patterns are presented.

Pattern-1: The experiment results tracking power, voltage, current using proposed VPSO-LF, PSO and HC algorithms are shown in Fig. 18 along with a screenshot of GMPP on the *P–V* curve, which is attached to each subfigure on the right side corner. The HC algorithm tracks a power 45.92 W and the time taken to reach this power is 2.4 s. From the HC results, steady-state oscillation more occurred due to the step size. So the power obtained using PSO algorithm is 46.78 W with a time of 7.6 s along with 13 iterations. From PSO, it is observed that the steady-state and transient oscillations are high due to the PV simulator operating with minimum voltage (i.e. PV simulator has own limits of voltage and current). Whereas the proposed VPSO-LF tracking power is 52.20 W with a tracking time of 3.2 s with 6 iterations; the operating point is close to that of the GMPP even under minimum voltage. The proposed VPSO-LF algorithm works better compared to PSO and HC algorithms.

Pattern-2: The tracking voltage, current and power of pattern-2 results along with GMPP on the *P–V* curve are shown in Fig. 19. On observing these results, it is clear that the tracking time is 1.6 s and 3 iterations are required to reach the global peak of 73.50 W for the proposed algorithm. On the other hand, the tracking time of PSO algorithm is 6.4 s and the number of iterations required to get global peak is 11, for a power of 72.24 W. The HC algorithm takes 8 s to track global peak and its iterations depends on step size for a power of 72.93 W. From this pattern, the tracking time and steady-state oscillations of HC algorithms are more compared to VPSO-LF and PSO algorithms; PSO algorithm takes more iterations, less

Table 6 Performance results of proposed, PSO and HC algorithms

Technique to extract maximum power	Rated power, W	Maximum power extracted from PV, W	Maximum voltage extracted from PV, V	Maximum current extracted from PV, A	Tracking time, s	Iterations required to reach GMPP	Maximum efficiency extracted from PV, %
proposed	53.47pattern-1	52.20	14.50	3.60	3.2	6	97.62
PSO		46.78	17.20	2.72	7.6	13	87.49
HC		45.92	17.80	2.58	2.4	—	85.88
proposed	74.17pattern-2	73.50	35.00	2.10	1.6	3	99.09
PSO		72.24	34.40	2.10	6.4	11	97.39
HC		72.93	33.00	2.21	8.0	—	98.32
proposed	94.61pattern-3	94.12	52.00	1.81	3.0	5	99.48
PSO		90.84	54.40	1.67	6.0	10	96.02
HC		91.69	49.30	1.86	8.1	—	96.92
proposed	114.71pattern-4	114.24	51.00	2.24	3.2	6	99.59
PSO		111.15	49.40	2.25	6.5	11	96.89
HC		107.13	55.80	1.92	5.6	—	93.39
proposed	149.33pattern-5	148.97	50.50	2.95	1.6	3	99.76
PSO		148.40	49.80	2.98	7.0	12	99.37
HC		146.05	53.50	2.73	7.0	—	97.80
proposed	160.93pattern-6	157.79	50.90	3.10	2.4	4	98.04
PSO		150.00	50.00	3.00	6.4	11	93.20
HC		158.17	52.90	2.99	4.0	—	98.28
proposed	149.69pattern-7	147.66	69.00	2.14	2.2	4	98.64
PSO		147.63	70.30	2.10	5.0	9	98.62
HC		132.96	74.70	1.78	4.0	—	88.82
proposed	181.06pattern-8	179.90	70.00	2.57	1.6	3	99.36
PSO		156.20	71.00	2.20	8.0	14	86.26
HC		169.00	65.00	2.60	4.0	—	93.33

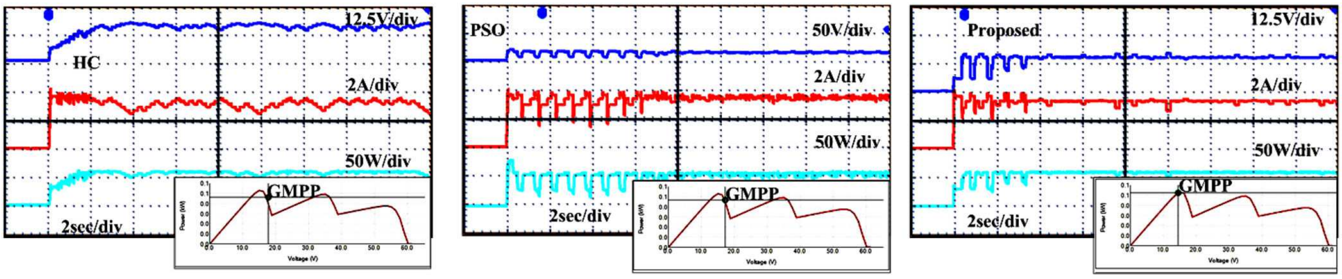


Fig. 18 *Experimental results of pattern-1*
(a) HC, ***(b)*** PSO, ***(c)*** Proposed

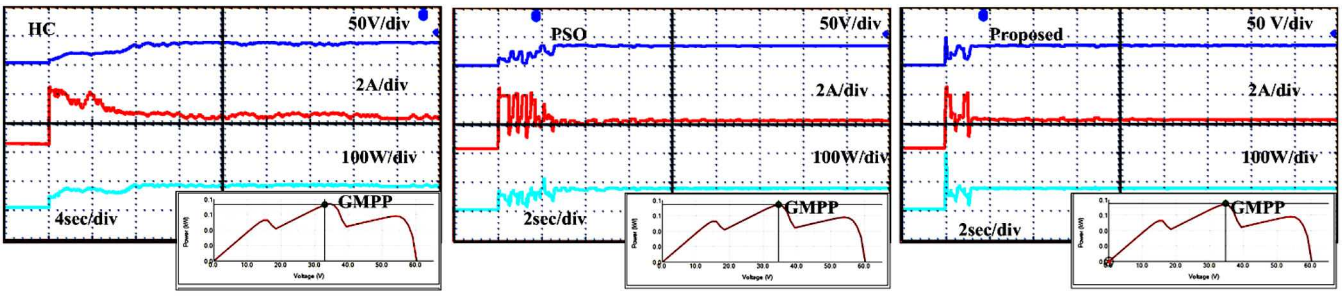
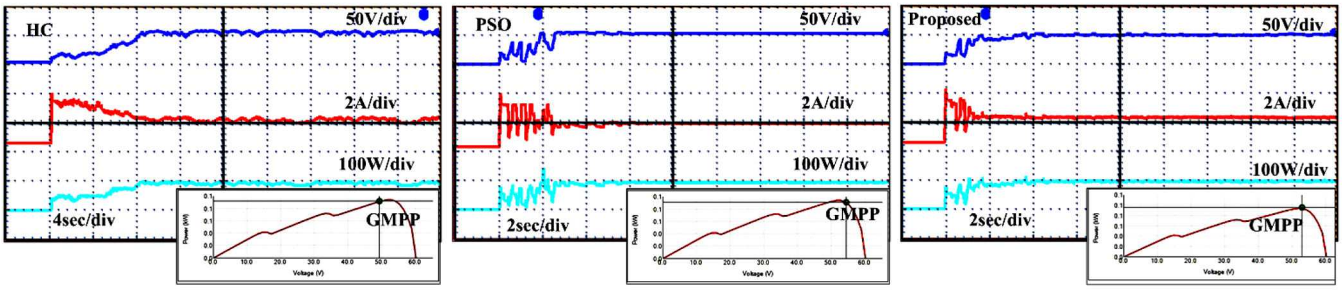


Fig. 19 *Experimental results of pattern-2*
(a) HC, ***(b)*** PSO, ***(c)*** Proposed

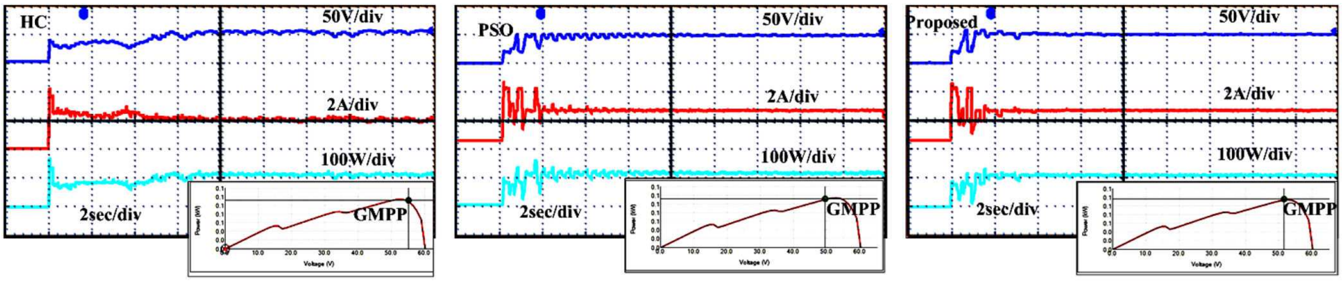
steady-state oscillations compared to HC. The steady-state power oscillations and iterations of the proposed VPSO-LF algorithm are fewer compared to PSO and HC algorithms. The performance results of VPSO-LF algorithm over PSO and HC algorithms are shown in Table 6.

Pattern-3: Pattern-3 tracking power, voltage and current results of three algorithms are shown in Fig. 20. The tracking time of VPSO-LF algorithm is 3 s, and the number of iterations required for GMPP is 5, the power obtained is 94.12 W. The PSO algorithm takes a tracking time of 6 s to reach the global peak 90.84 W with 10 iterations. The HC algorithm takes 8.1 s to reach the global peak of 91.69 W, but the steady-state oscillations are more. The advantage of the proposed algorithm that it is similar to the above patterns. The VPSO-LF algorithm takes low tracking time and fewer iterations compared to PSO and HC.



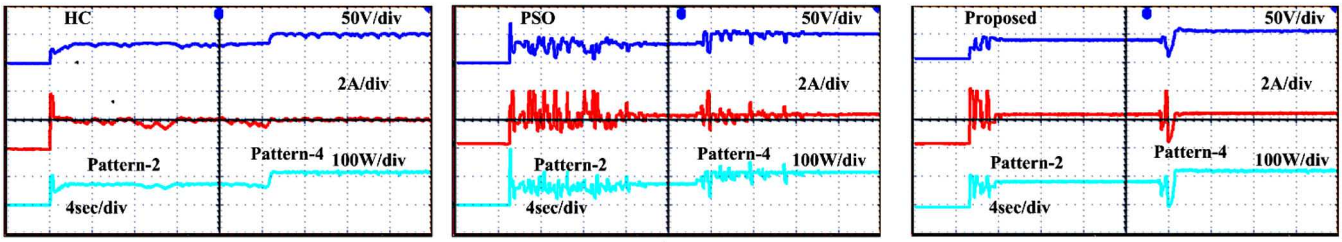
a *b* *c*

Fig. 20 *Experimental results of pattern-3*
(a) HC, ***(b)*** PSO, ***(c)*** Proposed



a *b* *c*

Fig. 21 *Experimental results of pattern-4*
(a) HC, ***(b)*** PSO, ***(c)*** Proposed



a *b* *c*

Fig. 22 *Experimental results changing pattern-2 to pattern-4*
(a) HC, ***(b)*** PSO, ***(c)*** Proposed

Pattern-4: The tracking voltage, current and power of the experimental results based on pattern-4 is shown in Fig. 21. The proposed algorithm tracks GMPP with 3.2 s, whereas the PSO and HC algorithms take 6.5 and 5.6 s of tracking time.

The iterations required for VPSO-LF are 6 and 11 for PSO, HC. The advantage of the proposed algorithm over PSO and HC is that it needs less tracking time, fewer iterations and low steady-state oscillations. The power levels of VPSO-LF, PSO and HC, are 114.24, 111.15 and 107.13 W.

Dynamics of pattern-2 to pattern-4: Its assignment is to verify whether the proposed VPSO-LF algorithm tracks GMPP when there is a sudden change of one pattern to another pattern of the PV system at a particular time. Like the proposed algorithm, this pattern is tested with pattern-2 and tracks GMPP at a steady-state point; after some time the fourth pattern is applied to the experiment through PV simulator, the proposed algorithm again re-initialises the initial parameters and tracks GMPP in less time compared to PSO and HC algorithms. So the proposed VPSO-LF algorithm works perfectly despite any change in irradiance of the PV system. The dynamics of PSO and HC algorithms are also verified with experimental results. The dynamic results of VPSO-LF, PSO and HC algorithms are shown in Fig. 22.

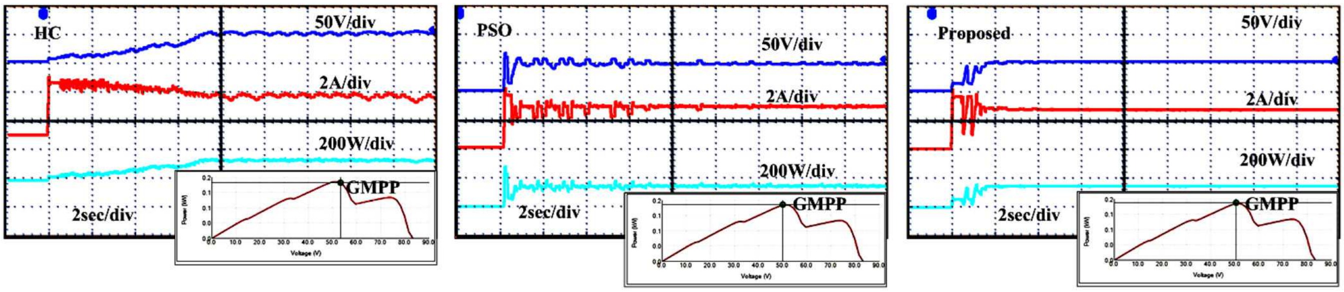
5.2 Results of 4S configuration

In 4S configuration of PV array, two patterns are considered under PSC, in order to verify the proposed VPSO-LF algorithm as having results similar to simulation results. The tracking power, voltage and current of pattern-5 results are shown in Fig. 23. The tracking power of pattern-5 by HC method is 146.05 W with tracking time of 7 s to reach GP, also shown its PV simulator screenshot of GMPP location on *P*–*V* curve of pattern-5 in each subfigure on the right side corner below. Similarly, with PSO method, the obtained tracking power of 148.40 W, with tracking time of 7 s and 12 iterations to reach the global peak. The proposed VPSO-LF algorithm takes tracking time of 1.6 s and 3 iterations to find the location of GMPP with power 148.97 W. Experimental results closely match simulation results. The 4S configuration of pattern-6 results is shown in Fig. 24. Using HC method tracking power is 158.17 W and it takes 4 s to reach a global point. The PSO method uses up tracking power of 150 W with 6.4 s and 11 iterations required to reach GMPP. The proposed method uses the tracking power of 157.79 W with a tracking time of 2.4 s and 4 iterations to reach GMPP. In 4S configurations also, the proposed algorithm overcomes the problems of PSO and HC, the results of which are presented in Table 6.

5.3 Results of 6S configuration

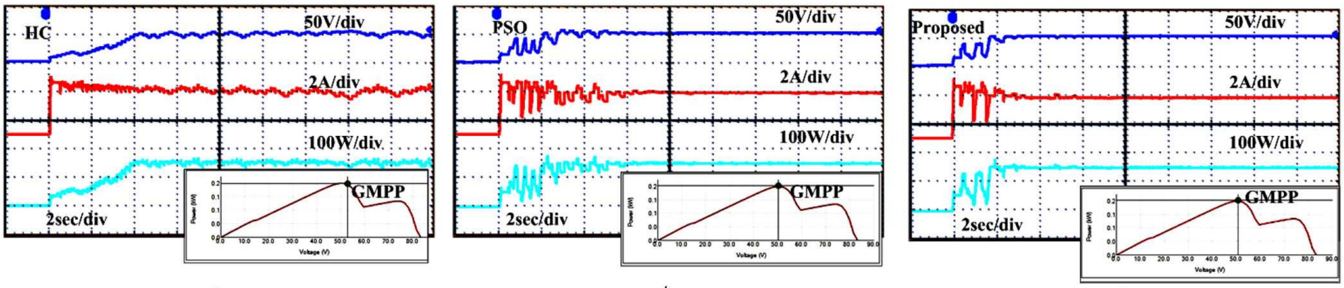
The 6S configuration of PV array consists of two patterns under PSC. The tracking power achieved by the HC method is 132.96 W with a tracking time of 4 s. The PSO method tracks power of 147.63 W in 5 s while 9 iterations are required to attain GP; the screenshot of the GMPP on the *P*–*V* curve on the right side below the corner of each subfigure is shown in Fig. 25. The tracking power achieved by the proposed method of pattern-7 is 147.66 W with a tracking time of 2.2 s with 4 iterations.

Pattern-8 tracking results are shown in Fig. 26. The tracking power achieved by the HC method is 169 W with a tracking time of 4 s. PSO method uses up 156.20 W has a tracking time of 8 s



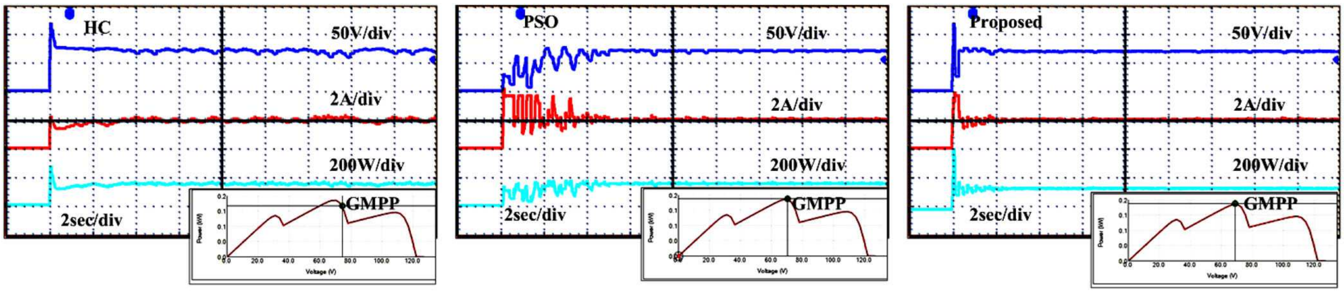
a *b* *c*

Fig. 23 *Experimental results of pattern-5*
(a) HC, ***(b)*** PSO, ***(c)*** Proposed



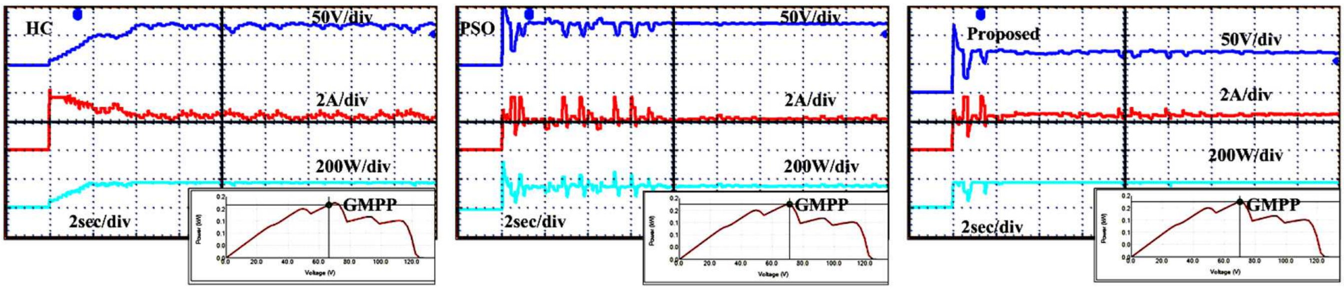
a *b* *c*

Fig. 24 *Experimental results of pattern-6*
(a) HC, ***(b)*** PSO, ***(c)*** Proposed



a *b* *c*

Fig. 25 *Experimental results of pattern-7*
(a) HC, ***(b)*** PSO, ***(c)*** Proposed



a *b* *c*

Fig. 26 *Experimental results of pattern-8*
(a) HC, ***(b)*** PSO, ***(c)*** Proposed

with 14 iterations but the proposed method tracks GMPP in just 1.6 s with 3 iterations and global power of 179.90 W. The performance results of 6S configuration are shown in Table 6.

6 Comparative study

The proposed VPSO-LF algorithm reduces tracking time, number of iterations, as well as steady-state oscillations around the global peak and has more tracking efficiency compared to PSO and HC algorithms. The velocity of PSO is updated with LF distribution in small steps in order to achieve convergence of the global peak without tuning parameters, but in PSO the velocity update uses three tuning parameters (w, C_1, C_2), because of which it is unable to converge at the global peak, and uses more iterations to reach GP. The comparison of velocity particle of VPSO-LF with PSO is shown in Fig. 8. The problems occurring in the HC algorithm are because of its step size, and its inability to tune its step size when a change of irradiance or PSC occur.

The performance results of the proposed algorithm with PSO and HC are explained clearly under eight patterns of PV array in Table 6. Two patterns are considered for the comparison of power and current of all three algorithms on the same time scale is shown in Fig. 27. Tracking power, tracking time, efficiency and iterations versus a number of patterns of PV array of all three algorithms are shown in Fig. 28. FPA [40] is mentioned in the introduction where

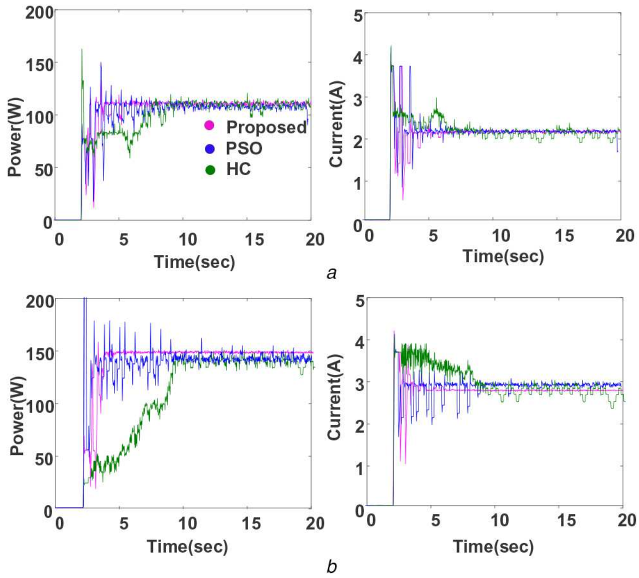


Fig. 27 *Comparisons of power and current of three algorithms*
(a) Pattern-4, ***(b)*** Pattern-6

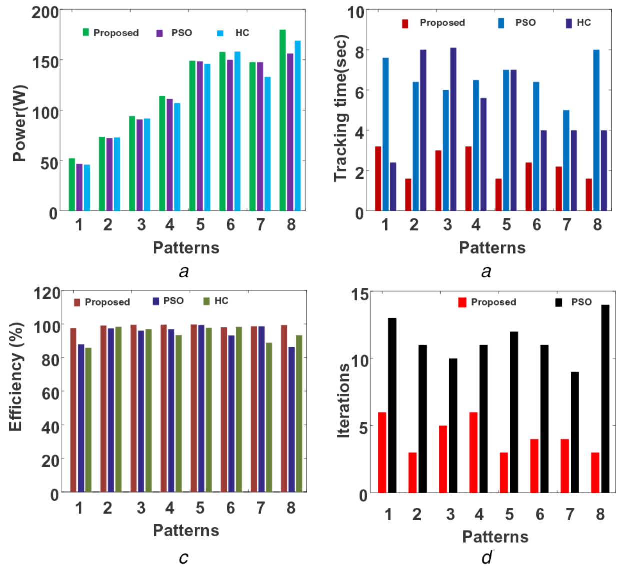


Fig. 28 *Comparative studies of*
(a) Power, ***(b)*** Tracking time, ***(c)*** Efficiency, ***(d)*** Iterations

Table 7 Qualitative performance of the proposed VPSO-LF with existing MPPT algorithms

Parameters	Method						
	PSO [15]	LPSO [20]	FPA [40]	ICS [21]	MPV-PSO [18]	HAPO & PSO [22]	VPSO-LF
tracking speed	moderate	fast	fast	moderate	fast	fast	fast
iterations	more	less	less	less	less	less	less
tuning parameters	3	1	nil	nil	2	nil	nil
initial particles	independent	independent	independent	independent	dependent	dependent	independent
no. of particles	5	5	5	4	3	3	3

it is established that the algorithm is unable to find a GP with fewer initial duty cycles, but the proposed algorithm in our study located GP with three duty initialisation very little time. LPSO [20] tracked GP with five initial particles and weight tuning parameter, but the proposed algorithm was implemented with no tuning parameter. MPV-PSO [18] discards the tuning of the weight of PSO, while also showings the nature of deterministic behaviour and adaptive and tuning of cognitive factors with the current position. HAPO &PSO [22] tracking speed is high but the initial particles are dependent on V_{oc}. The ICS [21] was considered four initial duties even though its tracking time is more when compared to the proposed method. These comparisons are shown in Table 7.

7 Conclusion

In this paper, the velocity of VPSO-LF algorithm was proposed, developed and validated for GMPP tracking of PV array under PSC. In the proposed algorithm, the velocity is updated with LF distribution to reach GMPP with low tracking time and reduced the number of iterations without any limitations on velocity. The proposed method also reduces steady-state oscillations around global peak effectively, initial duty independent of the PV system and also does not needs the tuning of velocity parameters. The testing of the proposed algorithm was carried out along with conventional PSO and HC to validate the results. From these results, the proposed VPSO-LF method gave better results than conventional PSO and HC methods. VPSO-LF can locate GP with any pattern of PV array, showing higher efficiency.

8 Acknowledgement

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9 References

[1] Selvakumar, S., Madhusmita, M., Koodalsamy, C.*, et al.*: 'High-speed maximum power point tracking module for PV systems', *IEEE Trans. Ind. Electron.*, 2019, **66**, (2), pp. 1119–1129

[2] Patel, H., Agarwal, V.: 'MATLAB-based modeling to study the effects of partial shading on PV array characteristics', *IEEE Trans. Energy Convers.*, 2008, **23**, (1), pp. 302–310

[3] Femia, N., Petrone, G., Spagnuolo, G.*, et al.*: 'Optimization of perturb and observe maximum power point tracking method', *IEEE Trans. Power Electron.*, 2005, **20**, (4), pp. 963–973

[4] Alajmi, B., Ahmed, K., Finney, S.*, et al.*: 'Fuzzy-logic-control approach of a modified hill-climbing method for maximum power point in microgrid standalone photovoltaic system', *IEEE Trans. Power Electron.*, 2011, **26**, (4), pp. 1022–1030

[5] 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**, (4), pp. 1154–1161

[6] Weidong, X., Dunford, W.G.: 'A modified adaptive hill climbing MPPT method for photovoltaic power systems'. IEEE Power Electron. Specialists Conf., Aachen, Germany, 2004, pp. 1957–1963

[7] Chee, W.T., Tim, C.G., Carlos, A.H.A.: 'An improved Maximum power point tracking algorithm with current-mode control for photovoltaic applications'. Int. Conf. Power Electron. Drives Syst., Kuala Lumpur, 2005, pp. 489–494

[8] Piegari, L., Rizzo, R.: 'Adaptive perturb and observe algorithm for photovoltaic maximum power point tracking', *IET Renew. Power Gener.*, 2010, **4**, (4), pp. 317–328

[9] Femia, N., Granozio, G., Petrone, G.*, et al.*: 'Predictive & adaptive MPPT perturb and observe method', *IEEE Trans. Aerosp. Electron. Syst.*, 2007, **43**, (3), pp. 934–950

[10] Tey, K.S., Mekhilef, S.: 'Modified incremental conductance algorithm for photovoltaic system under partial shading conditions and load variation', *IEEE Trans. Ind. Electron.*, 2014, **61**, (10), pp. 5384–5392

[11] Nguyen, T.L., Low, K.S.: 'A global maximum power point tracking scheme employing DIRECT search algorithm for photovoltaic systems', *IEEE Trans. Ind. Electron.*, 2010, **57**, (10), pp. 3456–3467

[12] Patel, H., Agarwal, V.: 'Maximum power point tracking scheme for PV systems operating under partially shaded conditions', *IEEE Trans. Ind. Electron.*, 2008, **55**, (4), pp. 1689–1698

[13] Alireza, K., Hossein, I.E., Behzad, A.: 'A new maximum power point tracking strategy for PV arrays under uniform and non-uniform insolation conditions', *Sol. Energy*, 2013, **91**, pp. 221–232

[14] Jubaer, A., Zainal, S.: 'An improved method to predict the position of maximum power point during partial shading for PV arrays', *IEEE Trans. Ind. Inf.*, 2015, **11**, (6), pp. 1378–1387

[15] Yi, H.L., Shyh, C.H., Jia, W.H.*, et al.*: 'A particle swarm optimization-based Maximum power point tracking algorithm for PV systems operating under partially shaded conditions', *IEEE Trans. Energy Conv.*, 2012, **27**, (4), pp. 1027–1035

[16] Kashif, I., Zainal, S.: 'A deterministic particle swarm optimization Maximum power point tracker for photovoltaic system under partial shading condition', *IEEE Trans. Ind. Electron.*, 2013, **60**, (8), pp. 3195–3206

[17] Babu, T.S., Rajasekar, N., Sangeetha, K.: 'Modified particle swarm optimization technique based maximum power point tracking for uniform and under partial shading condition', *Appl. Soft Comp.*, 2015, **34**, pp. 613–624

[18] Sen, T., Pragallapati, N., Agarwal, V.*, et al.*: 'Global maximum power point tracking of PV arrays under partial shading conditions using a modified particle velocity-based PSO technique,', *IET Renew. Power Gener.*, 2018, **12**, (5), pp. 555–564

[19] Jiang, L.L., Maskell, D.L., Patra, J.C.: 'A novel ant colony optimization-based maximum power point tracking for photovoltaic systems under partially shaded conditions', *Energy Build.*, 2012, **58**, pp. 227–236

[20] Prasanth, R.J., Rajasekar, N.: 'A new robust, mutated and fast tracking LPSO method for solar PV maximum power point tracking under partial shaded conditions', *Appl. Energy*, 2017, **201**, pp. 45–59

[21] Shi, J.Y., Xue, F., Qin, Z.J.*, et al.*: 'Improved global maximum power point tracking for photovoltaic system via cuckoo search under partial shaded conditions', *J. Power Electron.*, 2016, **16**, (1), pp. 287–296

[22] Kermadi, M., Salam, Z., Ahmed, J.*, et al.*: 'An effective hybrid maximum power point tracker of photovoltaic arrays for complex partial shading conditions', *IEEE Trans. Ind. Electron.*, 2018, **66**, (9), pp. 6990–7000

[23] 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**, (2), pp. 463–472

[24] Sundareswaran, K., Sankar, P., Nayak, P.S.R.*, et al.*: 'Enhanced energy output from a PV system under partial shaded conditions through artificial bee colony', *IEEE Trans. Sustain. Energy*, 2015, **6**, (1), pp. 198–209

[25] Mohanty, S., Subudhi, B., Ray, P.K.: 'A new MPPT design using grey wolf optimization technique for photovoltaic system under partial shading conditions', *IEEE Trans. Sustain. Energy*, 2016, **7**, (1), pp. 181–188

[26] Ram, J.P., Rajasekar, N.: 'A novel flower pollination based global maximum power point method for solar maximum power point tracking', *IEEE Trans. Power Electron.*, 2017, **32**, (11), pp. 8486–8499

[27] Hong, L., Duo, Y., Wenzhe, S.*, et al.*: 'An overall distribution particle swarm optimization MPPT algorithm for photovoltaic system under partial shading', *IEEE Trans. Ind. Electron.*, 2019, **66**, (1), pp. 265–275

[28] Ram, J.P., Pillai, D.S., Rajasekar, N.*, et al.*: 'Detection and identification of global maximum power point operation in solar PV applications using a hybrid ELPSO-P&O tracking technique', *IEEE J. Emerg. Sel. Top. Power Electron.*, DOI 10.1109/JESTPE.2019.2900999

[29] Venkata, R.K., Muralidhar, N.B.: 'A novel global MPP tracking scheme based on shading pattern identification using artificial neural networks for photovoltaic power generation during partial shaded condition', *IET Renew. Power Gener.*, 2019, **13**, (10), pp. 1647–1659

[30] Mohammed, A.H., Abhinandan, J., Abu, T.*, et al.*: 'Fast and precise global maximum power point tracking techniques for photovoltaic system', *IET Renew. Power Gener.*, 2019, **13**, (14), pp. 2569–2579

[31] Villalva, M.G., Gazoli, J.R., Filho, E.R.: 'Comprehensive approach to modeling and simulation of photovoltaic arrays', *IEEE Trans. Power Electron.*, 2009, **24**, (5), pp. 1198–1208

[32] Eberhart, R., Kennedy, J.: 'A new optimizer using particle swarm theory'. Proc. Int. Symp. Micro Machine Human Sci., Nagoya, Japan, 1995, pp. 39–43

[33] Miyatake, M., Veerachary, M., Toriumi, F.*, et al.*: 'Maximum power point tracking of multiple photovoltaic arrays: a PSO approach', *IEEE Trans. Aerosp. Electron. Syst.*, 2011, **47**, (1), pp. 367–380

[34] Hakli, H., Uguz, H.: 'A novel particle swarm optimization algorithm with Lévy flight', *Appl. Soft Comput.*, 2014, **23**, pp. 333–345

[35] Chechkin, A.V., MetzlEr, R., Klafter, J.*, et al.*: '*Introduction to the theory of Lévy flights*' (John Wiley & Sons, Hoboken, New Jersey, United States 2008), pp. 129–162

[36] Yang, X.-S., Deb, S.: 'Cuckoo search via Lévy flights'. World Congress on Nature & Biologically Inspired Comput., Coimbatore, India, 2009, pp. 210–214

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

[38] Jensi, R., Wiselin, J.G.: 'An enhanced particle swarm optimization with Levy flight for global optimization', *Appl. Soft Comput.*, 2016, **43**, (C), pp. 248–261

[39] Ghasemi, M.A., Mohammadian, F.H., Parniani, M.: 'Partial shading detection and smooth maximum power point tracking of PV arrays under PSC', *IEEE Trans. Power Electron.*, 2016, **31**, (9), pp. 6281–6292

[40] Prasanth, R.J., Rajasekar, N.: 'A new global maximum power point tracking technique for solar photovoltaic (PV) system under partial shading conditions (PSC)', *Energy*, 2017, **118**, pp. 512–525