A New MPPT Design Using Grey Wolf Optimization Technique for Photovoltaic System Under Partial Shading Conditions

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***Abstract*—This paper presents a maximum power point tracking (MPPT) design for a photovoltaic (PV) system using a grey wolf optimization (GWO) technique. The GWO is a new optimization method which overcomes the limitations such as lower tracking efficiency, steady-state oscillations, and transients as encountered in perturb and observe (P&O) and improved PSO (IPSO) techniques. The problem of tracking the global peak (GP) of a PV array under partial shading conditions (PSCs) is attempted employing the GWO-based MPPT technique. The proposed scheme is studied for a PV array under PSCs which exhibits multiple peaks and its tracking performance is compared with that of two MPPT algorithms, namely P&O-MPPT and IPSO-MPPT. The proposed GWO-MPPT algorithm is implemented on a PV system using MATLAB/SIMULINK. Furthermore, an experimental setup is developed to verify the efficacy of the proposed system. From the obtained simulation and experimental results, it is observed that the proposed MPPT algorithm outperforms both P&O and IPSO MPPTs.**

***Index Terms*—Grey wolf optimization (GWO), maximum power point tracking (MPPT), partial shading conditions (PSCs), photovoltaic (PV).**

I. Introduction

VARIOUS maximum power point tracking (MPPT) algorithms were discussed in literature [1] about the occurrence of mismatched nonuniform insolation resulting in decrease in photovoltaic (PV) output power, and the hot-spot generated damages the PV cells. Since the dynamics of the PV system under partial shading is time varying, MPPT design for PV power system should be equipped with features such as tracking global maximum power point (GMPP) at different conditions, e.g., shading, degradation of PV cell, and adaptability to P–V characteristics change in PV array, smooth, and steady tracking behavior.

A number of MPPT techniques such as hill climbing (HC) [2], perturb and observe (P&O) [2]–[4], and incremental conductance (IC) [5] have been proposed for improving the efficiency of the PV system. The HC method uses a perturbation in the duty ratio of the power converter and the P&O method uses a perturbation in the operating voltage of the PV system [2]–[4]. Both these methods yield oscillations at maximum power point (MPP) owing to the fact that the perturbation continuously changes in both directions to maintain the MPP resulting in power loss. The two influencing parameters in P&O algorithm, namely perturbation rate and perturbation size, are discussed in [4]. To reduce these oscillations and improve the module efficiency, the IC method was proposed [5] which reduced the oscillations but not completely. Both P&O and IC methods fail during those time intervals characterized by changing atmospheric conditions [6], [7].

A few improved IC algorithms were also proposed to improve the MPP tracking capability during fast-changing irradiance level and load [8], [9]. To achieve a fast MPP tracking response, a simple trigonometric rule has been presented in [10] to establish relationship between the load line and I–V curve. A dynamic MPPT controller for PV systems under fast-varying insolation and PSCs is proposed in [11], which uses a scanning technique to determine the maximum power-delivering capacity of the panel at a given operating condition.

The focus of the research here is to determine the global peak (GP) during PSCs; in order to alleviate some of the issues like lower tracking efficiency and oscillations generated in the PV output power, an alternative approach is to employ evolutionary algorithm (EA) techniques, which has the capability to handle nonlinear objective functions. Metaheuristic optimization methodologies such as particle swarm optimization (PSO) [12], and firefly [13] have been extensively used for various engineering applications. Recently, Mirjalili *et al.* have developed a metaheuristic algorithm known as grey wolf optimization (GWO) [14]. This algorithm is inspired by grey wolves to attack preys for hunting purpose.

Further, several works are reported in literature on an alternative soft computing method known as grey wolf optimization which is attracting considerable interests from the research community compared to other optimization techniques because it is more robust and exhibits faster convergence. Furthermore, it requires fewer parameters for adjustment and less operators compared to other evolutionary approaches, which is an advantage when rapid design process is considered [14]. After a thorough literature survey, it is observed that GWO has not been exploited for designing an MPPT. Hence, this work attempts to exploit the GWO for designing an MPPT to obtain efficient tracking performance under PSCs.

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This paper is organized as follows. Section II describes about the characteristics of the PV system under PSCs and the system description showing I–V and P–V curves of partially shaded modules. Section III describes the proposed GWO-based MPPT algorithm to track the GP and Sections IV presents the simulation and experimental results. Finally, conclusion is provided in Section V.

II. Characteristics of a PV System Under PSCs

A. Basic Characteristics of a PV Cell

A PV cell can be represented by an equivalent single diode model [2]. The symbols used in the model are defined as follows:

I_{pv} PV current source;
D a diode connected in parallel to the current source;
R_s the sum of resistances due to all the components that come in path of current which is desirable to be as low as possible;
R_p to represent the leakage across the P–N junction which is desirable to be as high as possible;
I difference between the photocurrent I_{pv} and the diode current I_D, which is given by,

$$I = I_{pv} - I_0 \left[\exp\left(\frac{qV + qR_sI}{N_s k_s Ta} - 1\right)\right] - \frac{V + R_sI}{R_p} \quad (1)$$

where I_0 is the saturation current, a is diode ideality factor, k_s is Boltzmann's constant, q is charge of an electron, T is temperature in kelvin, and N_s is the number of cells in series.

B. System Description

A PV array consists of several PV modules connected in series to produce a higher voltage and in parallel to increase the current. During PSCs, multiple peaks, i.e., local and global maxima points are observed in the P–V characteristics curve due to the presence of bypass diodes. The presence of bypass diode connected in parallel to each PV module during PSCs reduces the probability of hot-spot during which the shaded module behaves as a load instead of generating power. Two different PV arrays are considered in this work and are shown in Figs. 1 and 2. A configuration consisting of four modules in series (4S configuration) having two different shading patterns with their P–V curves is shown in Fig. 1. The second PV configuration that has two series modules connected in parallel with another two series modules (2S2P configuration) having two different shading patterns with their respective P–V curves are shown in Fig. 2.

III. GWO and its Application in MPPT Design

A. Grey Wolf Optimization

The GWO algorithm imitates the leadership hierarchy and hunting mechanism of grey wolves in nature proposed by Mirjalili *et al.* [14]. Grey wolves are considered to be at the top of food chain and they prefer to live in a pack. Four types of grey wolves such as alpha (α), beta (β), delta (δ), and omega (ω) are employed for simulating the leadership hierarchy. In order to mathematically model the social hierarchy of wolves while designing GWO, we consider the fittest solution as the alpha (α). Consequently, the second and third best solutions are named as beta (β) and delta (δ), respectively. The rest of the candidate solutions are assumed to be omega (ω). Fig. 3 shows three main steps of GWO algorithm, namely hunting, chasing,

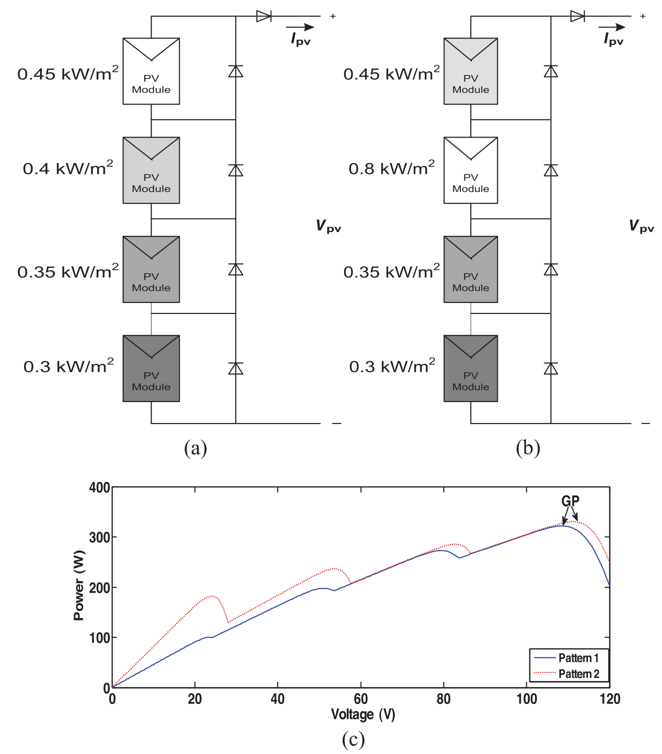

Fig. 1. 4S configuration under different shading patterns. (a) Pattern 1. (b) Pattern 2. (c) P–V curves under PSCs.

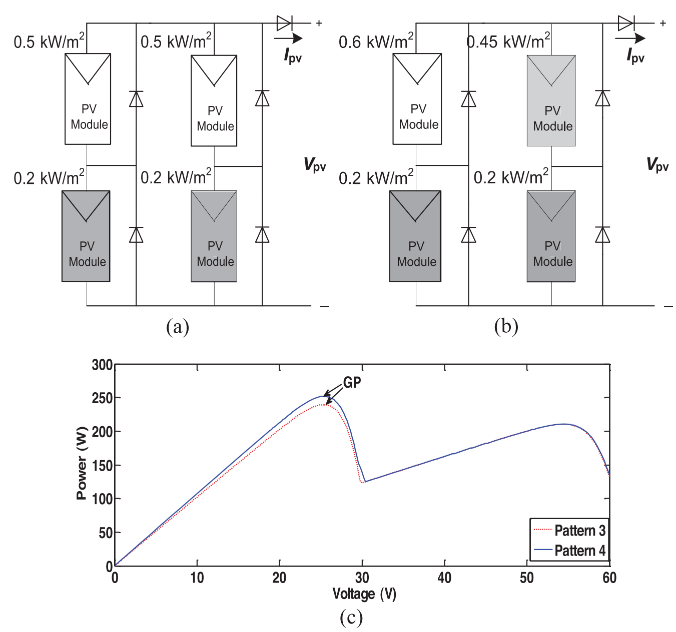

Fig. 2. 2S2P configuration under different shading patterns. (a) Pattern 3. (b) Pattern 4. (c) P–V curves under PSCs.

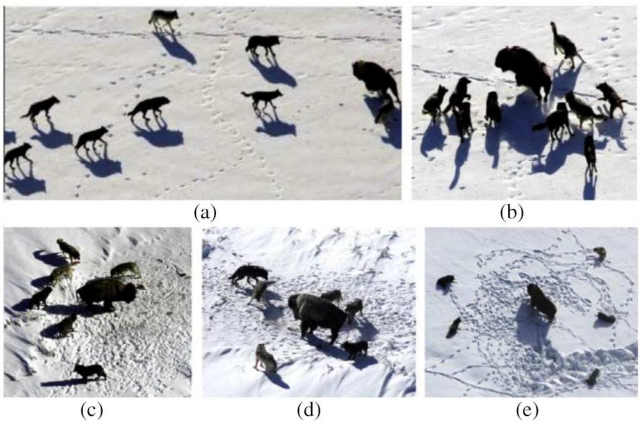

Fig. 3. Hunting behavior of grey wolves: (a)–(c) chasing and tracking prey; (d) encircling prey; and (e) attacking prey.

and tracking for prey, encircling prey, and attacking prey which are implemented to design GWO for performing optimization. Grey wolves encircle a prey during the hunt and the encircling behavior can be modeled by the following equations:

$$\vec{D} = |\vec{C} \cdot \vec{X}_p(t) - \vec{X}_p(t)| \tag{2}$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A} \cdot \vec{D} \tag{3}$$

where t denotes the current iteration, $\boldsymbol{D}$, $\boldsymbol{A}$, and $\boldsymbol{C}$ denote coefficient vectors, $\boldsymbol{X}_p$ is the position vector of the prey, and $\boldsymbol{X}$ indicates the position vector of grey wolf. The vectors $\boldsymbol{A}$ and $\boldsymbol{C}$ are calculated as follows:

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \tag{4}$$

$$\vec{C} = 2 \cdot \vec{r}_2 \tag{5}$$

where components of a linearly decreases from 2 to 0 during the course of iterations and $\boldsymbol{r}_1$, $\boldsymbol{r}_2$ are random vectors in [0, 1]. The hunt is usually guided by alpha called leaders followed by beta and delta which might also participate in hunting occasionally. Delta and omega take care of the wounded wolves in the pack. Therefore, we refer alpha as the candidate solution having better knowledge about the location of prey. The grey wolves finish the hunt by attacking the prey when it stops moving.

B. *Application of GWO for MPP Tracking*

Fig. 4 shows the block diagram of the proposed MPPT scheme for the PV system. For number of grey wolves, i.e., duty ratios, the controller measures $V_{\rm pv}$ and $I_{\rm pv}$ through sensors and computes the output power. The flowchart of the proposed GWO-based MPPT algorithm is shown in Fig. 5.

During partial shading, the P–V curve is categorized by multiple peaks having various local peaks (LPs) and one GP. It is to note that when the wolves find the MPP, their correlated coefficient vectors become nearly equal to zero. In the proposed method, an attempt has been made to combine GWO with direct duty-cycle control, i.e., at the MPP, duty cycle is sustained at a constant value which in turn reduces the steady-state oscillations that exist in conventional MPPT techniques and lastly, the power loss due to oscillation is reduced resulting in higher system efficiency. To implement the GWO-based MPPT, duty

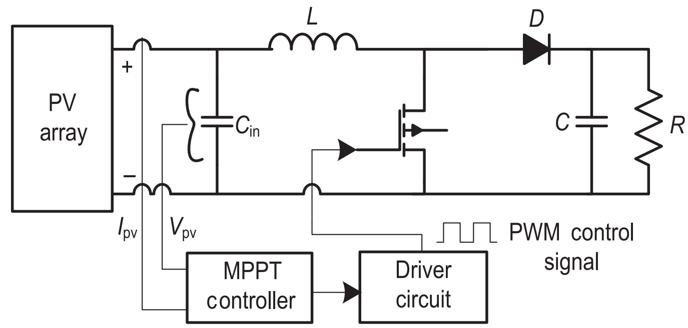

Fig. 4. Block diagram of the proposed MPPT method.

cycle D is defined as a grey wolf. Therefore, (3) can be modified as follows:

$$D_i(k+1) = D_i(k) - A \cdot D. \tag{6}$$

Thus, the fitness function of the GWO algorithm is formulated as

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

where P represents power, d is duty cycle, i is the number of current grey wolves, and k is the number of iterations.

IV. Results and Discussion

A. *Simulation Results*

To evaluate the performance of the proposed GWO-based metaheuristic MPPT algorithm, its performances were compared with P&O and improved PSO (IPSO) MPPT algorithms. All the above three algorithms were implemented under PSCs and rapidly changing insolation level for both 4S and 2S2P configurations. For simulation studies, the parameters taken for modeling single diode model of a PV module at nominal conditions are chosen as $P_{\rm max} = 200$ W, $V_{\rm oc} = 32.8$ V, $I_{\rm sc} = 8.21$ A, $V_{\rm mp} = 26.3$ V, and $I_{\rm mp} = 7.61$ A. The components for the designed converter used in simulation and experimental setup are chosen as $L = 10$ mH, $C_{\rm in} = 100$ μF, $C = 330$ μF, $V_{\rm in} = (0\text{–}130$ V), $V_{\rm out} = 300$ V, $f_s = 25$ kHz, and output voltage ripple is $\leq 1\%$. The parameters of IPSO algorithm are $w_{\max} = 1$, $w_{\min} = 0.1$, $c_{1,\max} = 2$, $c_{1,\min} = 1$, $c_{2,\max} = 2$, $c_{2,\min} = 1$, and GWO algorithm is a which linearly decreases from 2 to 0.

The power, voltage, and current for the 4S configuration with PSCs employing GWO, IPSO, and P&O are shown in Fig. 6. In the simulation study, pattern 1 is made to exist for first 0.1 s and the second pattern appears for next 0.1 s. In pattern 1, GWO-based MPPT converges to the GP of 319.4 W, IPSO tracks the GP of 319.2 W, and the P&O algorithm converges to LP of 100.2 W as it is unable to differentiate between local and GPs resulting in steady-state oscillations, i.e., the operating point oscillates around the MPP giving rise to power loss and also results in slowing down the speed of response of the algorithm and reduces the efficiency of the PV system. When shading pattern is changed to pattern 2 at 0.1 s, the MPPT techniques get restarted and GWO-based MPPT is able to locate the GP of 329.6 W, IPSO tracks GP of 329.5 W, and P&O fails

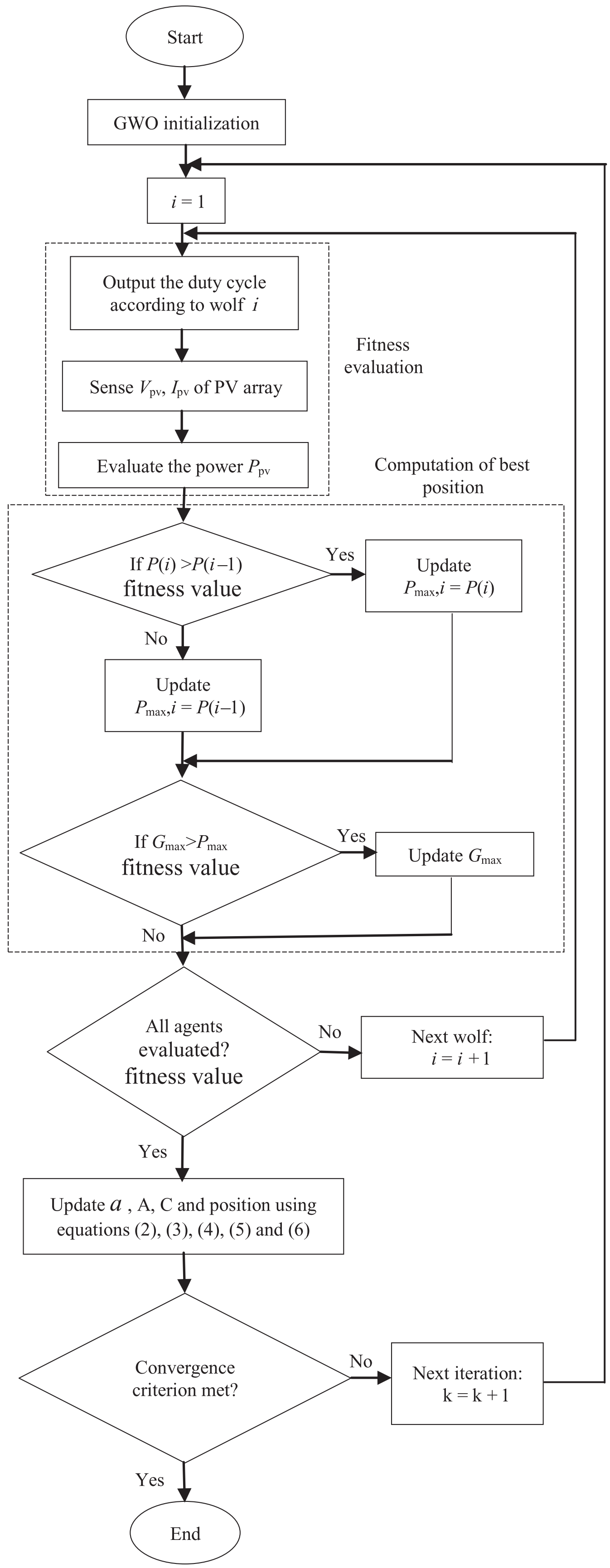

Fig. 5. Flowchart of the proposed algorithm.

to reach GP and gets settled at LP of 180 W. From the above results, it is concluded that the proposed GWO-based MPPT yields higher tracking speed and the oscillations disappear quickly as compared to other two methods, namely IPSO and P&O.

The simulation is now repeated for 2S2P configuration having two different patterns, namely patterns 3 and 4. The GWO-based MPPT reaches GP of 239.1 W, IPSO tracks GP of 239.05 W, and P&O algorithm reaches GP of 234 W anonymously as it tracks the peak which comes in contact first, i.e., it may be a GP or LP resulting in oscillations around MPP. All the above findings are implemented for existence of pattern 3 which appears for 0.1 s and pattern 4 appears for next 0.1 s. For pattern 4, the GWO-based MPPT locates the GP of 251.6 W, IPSO locates GP at 251.5 W, and P&O gets settled to the GP of 247 W as before in pattern 3 resulting in oscillations around the MPP. The tracking curves are shown in Fig. 7.

The simulation results presented in Figs. 6 and 7 envisage that the GWO-based MPPT can handle partial shading efficiently and it outperforms both P&O and IPSO with respect to faster convergence to GP, tracking speed, reduced steady-state oscillations, and higher tracking efficiency. The simulation results presented in Figs. 6 and 7 are briefly summarized in Tables I and III. The MPPT tracking efficiency is calculated as the ratio between average output power obtained at steady state and maximum available power of the PV array under certain shading pattern [13]. Further, a qualitative comparison among various fast-converging MPPT methods is presented in Table II. From Tables III and I, it is seen that the GWO-based MPPT outperforms over the other two MPPT methods.

To ensure the effectiveness of the proposed MPPT algorithm, different loads such as an R–L load (50 Ω, 15 mH) are connected in place of resistive load and are studied for pattern 1. Fig. 8 compares the response of two different types of loads (R and R–L load) from which it is seen in both the cases, the proposed MPPT is efficient enough to converge to the GP successfully. Usually, for R load fast response is observed compared to any other loads. However, it is seen from Fig. 9 that GWO is successful in providing similar tracking response.

B. Experimental Results

To validate the effectiveness of the proposed GWO-based MPPT, experiments were carried out on real PV array for both 4S and 2S2P configurations. Four 40 W solar modules of Sukam make are used in this experiment having rating of each module as $V_{mp} = 17.15$ V, $I_{mp} = 2.33$ A, $V_{oc} = 21.2$ V, and $I_{sc} = 2.55$ A, respectively. To create partial shading, transparent sheets of different shapes were placed on PV modules. Here, dSPACE1104 is used as a controller having various ADC and DAC channels to generate PWM signals which are based on 603 power PC floating point processor running at 250 MHz and a slave DSP subsystem based on TMS320F240 DSP and Hall effect sensor is used to sense the voltage and current of the PV array before sending it to the controller. Fig. 9 shows the experimental setup of the proposed system.

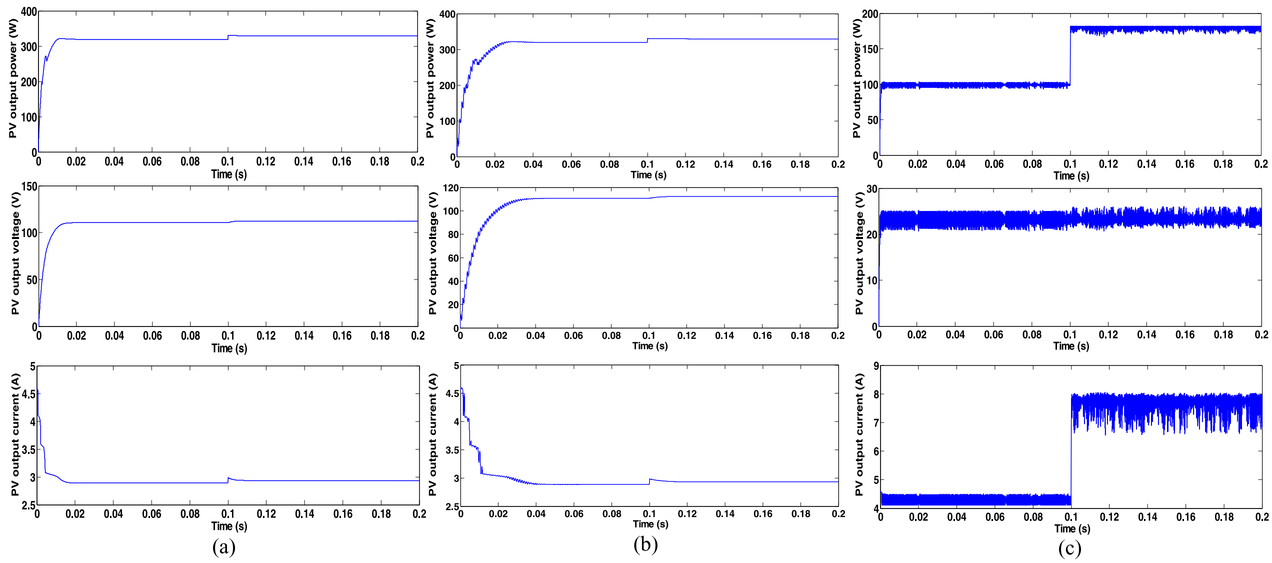

Fig. 6. Tracking curves for 4S configuration. (a) GWO-based MPPT. (b) IPSO-based MPPT. (c) P&O-based MPPT.

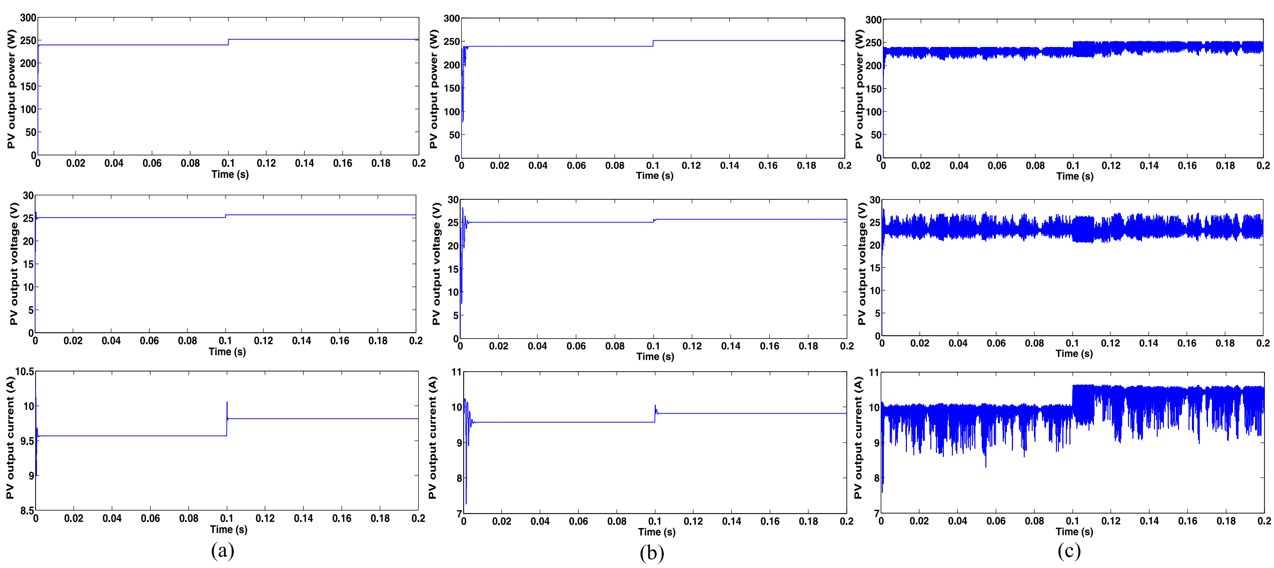

Fig. 7. Tracking curves for 2S2P configuration. (a) GWO-based MPPT. (b) IPSO-based MPPT. (c) P&O-based MPPT.

TABLE I
PERFORMANCE COMPARISON OF THE PROPOSED MPPT METHOD FOR 2S2P CONFIGURATION

Shading pattern	Maximum power from P–V curve (W)	Tracking techniques	Maximum power (W)	Maximum voltage (V)	Maximum current (A)	%Tracking efficiency
3	239.3	P&O	234	24	9.75	97.78
		IPSO	239.05	25	9.562	99.89
		GWO	239.1	25.01	9.56	99.91
4	251.8	P&O	247	23.9	10.3	98.09
		IPSO	251.5	25.64	9.808	99.88
		GWO	251.6	25.64	9.812	99.92

The two distinct patterns are shown in Fig. 10(a) marked as pattern 5 having GP of 113.8 W with two LPs and pattern 6 possess GP of 143.5 W with one LP. The experimentally determined tracking curves are shown in Fig. 10(b)–(d). The tracking curves show that GWO and IPSO-based MPPT converge to the GP of 113.8 W, whereas P&O gets trapped to LP of 53.44 W. The tracking speed of GWO is faster than IPSO since it takes 3.18 s to reach GP compared to IPSO which takes 7.9 s for global convergence. When the shading pattern 5 changes to pattern 6, the current MPPT restarts the search process for the

TABLE II
QUALITATIVE COMPARISON OF THE PROPOSED WITH OTHER FAST-CONVERGING MPPT TECHNIQUES

Type	P&O	IPSO	[9]	[13]	Proposed
Tracking speed	Slow	Medium	Fast	Fast	Very fast
Transient power fluctuation	Low	High	Moderate	Moderate	Low
Tracking accuracy	Low	Accurate	Highly accurate	Highly accurate	Highly accurate
Convergence to GP	Tracks which comes in contact first (LP or GP)	Yes	Yes	Yes	Yes
No. of tuning parameters	1	6	1	2	1
Steady state oscillations	Large	Zero	Zero	Zero	Zero
Power efficiency	High (uniform insolation) low (PSCs)	High	High	High	High
Implementation complexity	Low	Medium	Medium	Medium	Medium
Dynamic response	Poor	Good	Good	Good	Good

TABLE III
PERFORMANCE COMPARISON OF THE PROPOSED MPPT METHOD FOR 4S CONFIGURATION

Shading pattern	Maximum power from P–V curve (W)	Tracking techniques	Maximum power (W)	Maximum voltage (V)	Maximum current (A)	%Tracking efficiency
1	320	P&O	100.2	24.2	4.14	31.30
		IPSO	319.2	110.52	2.888	99.75
		GWO	319.4	110.55	2.889	99.81
2	330	P&O	180	23.07	7.80	54.54
		IPSO	329.5	112.3	2.934	99.84
		GWO	329.6	112.3	2.934	99.87

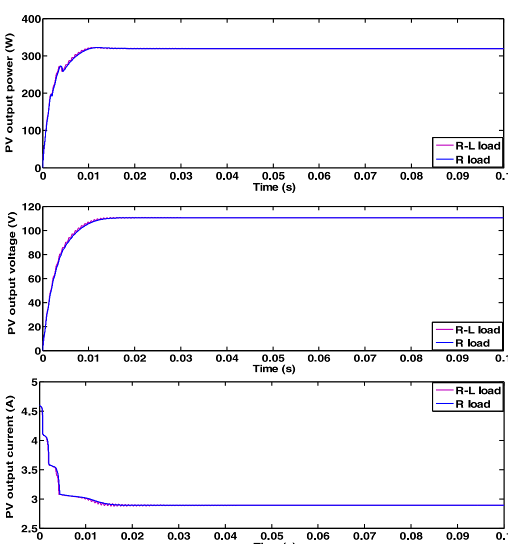

Fig. 8. Tracking curves for pattern 1 showing response of proposed MPPT having R and R–L load under PSCs.

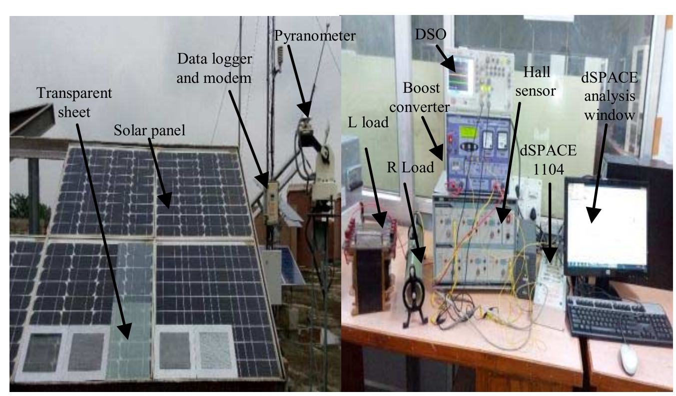

Fig. 9. Experimental setup for the proposed system.

new MPP from the new P–V curve. The tracking curves of GWO and IPSO-based MPPT reach GP of 143.5 W, whereas P&O gets trapped to LP of 65.32 W.

In order to validate the effectiveness of the proposed MPPT for a different random pattern, experiments were carried out for 2S2P configuration having two types of shading as shown in Fig. 11(a) as pattern 7 having GP of 77.98 W and LP of 47 W and pattern 8 have GP of 58.25 W and LP of 46.64 W, respectively. The experimentally determined MPPT curves employing the proposed and existing methods are shown in Fig. 11(b)–(d). The tracking curves of the proposed and IPSO MPPT are able to converge to GP of 77.98 W and P&O by chance settles to the GP resulting in oscillations. After sometime when the shading pattern changes to a new P–V curve marked as pattern 8, once again the three algorithms search the P–V curve for a new MPP. The curves of the proposed MPPT and IPSO-based MPPT converge to the GP of 58.25 W and P&O gets trapped at a local optimum value of 46.64 W.

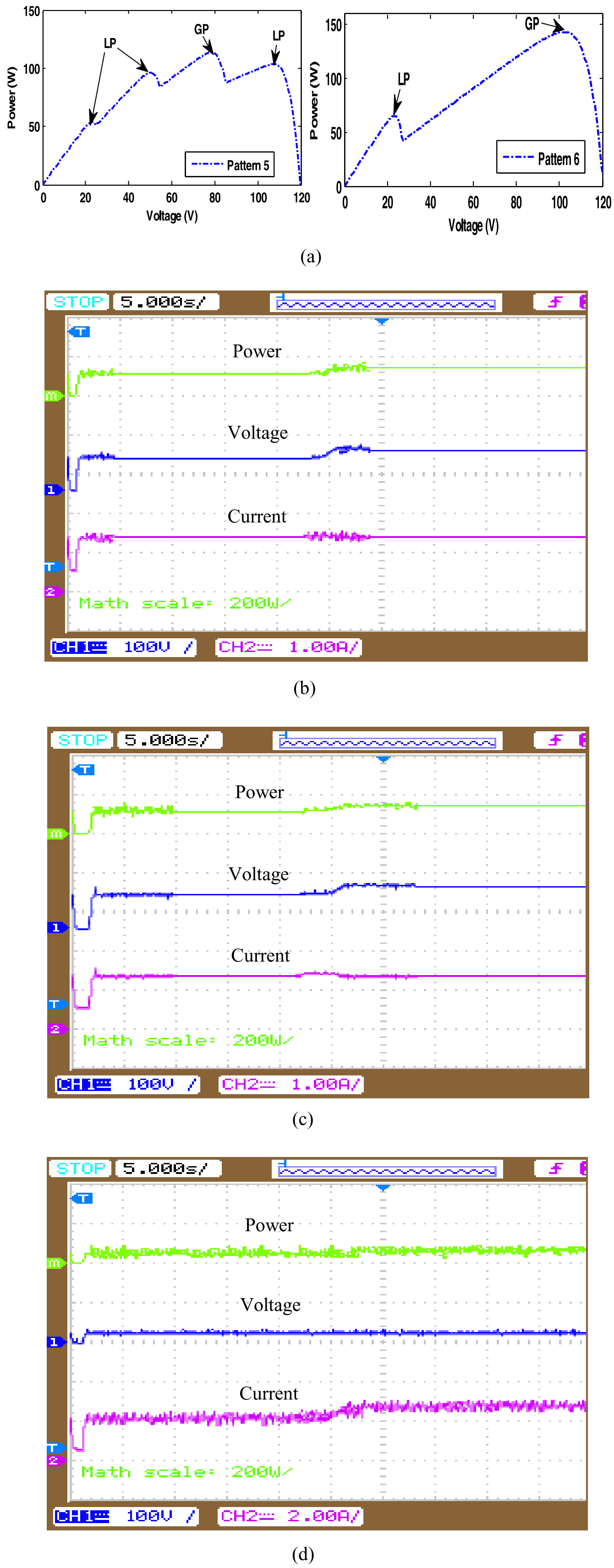

Fig. 10. Experiment results for 4S configuration. (a) P–V curves tracking curves using (b) GWO, (c) IPSO, and (d) P&O.

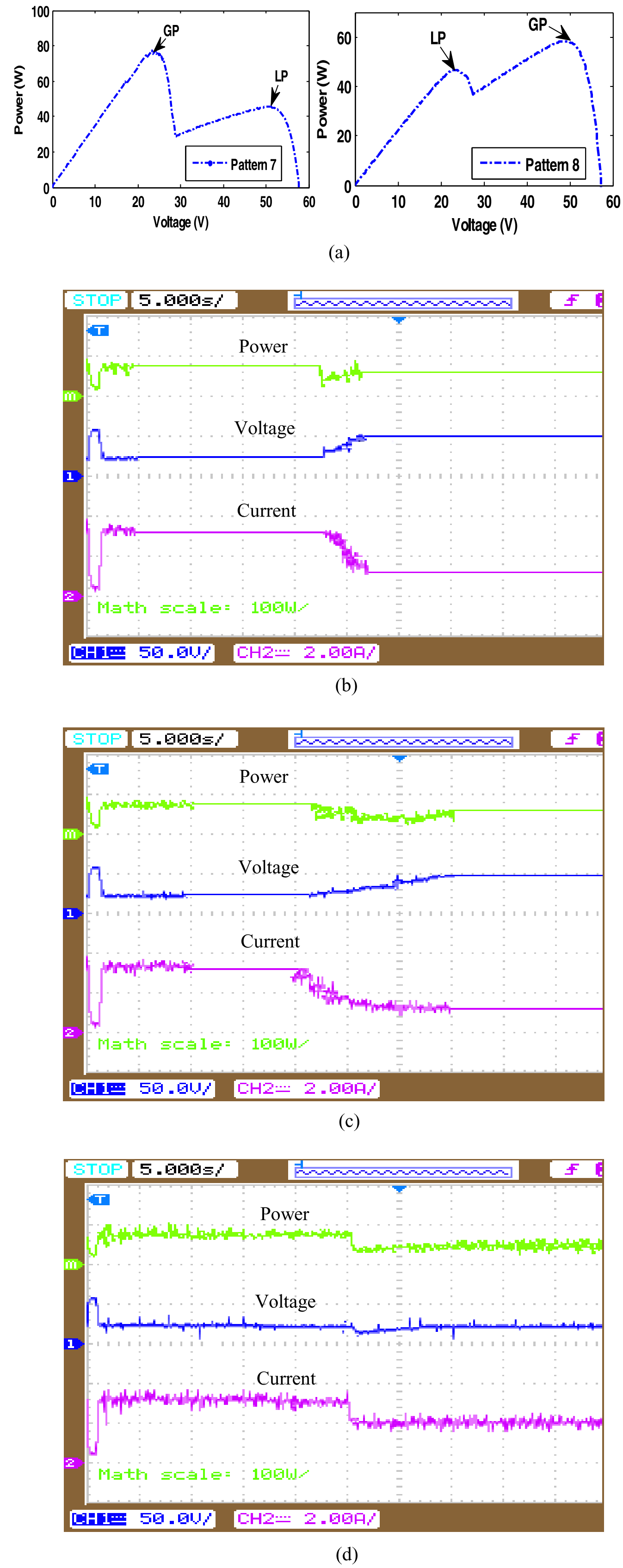

Fig. 11. Experiment results for 2S2P configuration. (a) P–V curves tracking curves using (b) GWO, (c) IPSO, and (d) P&O.

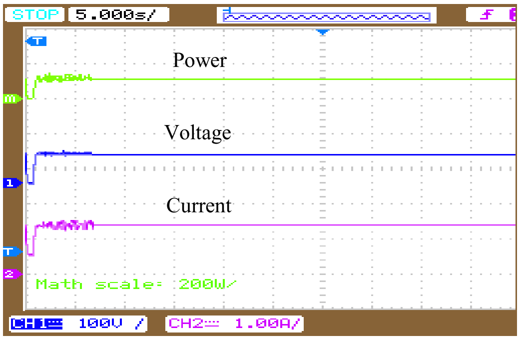

Fig. 12. Experiment results for pattern 5 showing response of proposed MPPT under R–L load.

To verify that the effectiveness of the proposed MPPT algorithm is working accurately under R–L load, experiments were carried out for pattern 5. Fig. 12 shows that the settling time increases, but the performance of the proposed MPPT remains the same for convergence toward the GP.

Figs. 10 and 11 show that the proposed method can successfully detect the shading pattern variations and reinitialize the MPPT process exhibiting superior performance in terms of faster convergence to GP, reduced steady-state oscillations, and faster tracking in PV system under PSCs.

V. Conclusion

This paper proposed a new evolutionary computing approach called grey wolf optimization to design a maximum power extraction algorithm for PV systems to work under PSCs. In view of assessing the effectiveness of this new MPPT (grey-wolf-based MPPT), its performance was compared with two existing MPPTs, namely P&O and IPSO-based MPPT methods and from the obtained results, it was found that the GWO-based MPPT exhibits superior performance compared to other two MPPTs.

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