PV Output Power Enhancement using Whale Optimization Algorithm under Normal and Shading Conditions

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Abstract- This paper deals with whale hunting behaviour inspired whale optimization algorithm (WOA) for tracking maximum power from the solar photovoltaic (PV) system. Maximum power point tracking (MPPT) controller has become an essential requirement for tracking the actual power present in solar PV system. In literature, various optimization techniques have been proposed for normal and partial shading conditions (PSC). But the problem in the conventional methods is tracking peak power under shading conditions is not assurance due to the presence of many peaks in a shading conditions. Because the local peaks are presented very close to global peaks. The results of conventional algorithms get failed with local peaks instead of tracking global peak power particularly in shading conditions. In this paper, a new WOA algorithm has been proposed which has the ability to reach the peak power presented in solar PV panel under different climatic conditions. In further, the proposed WOA algorithm has been investigated in MATLAB/Simulink model and comparison has been made with different MPPT algorithms, namely, Perturb and Observe (PO), grey wolf optimization (GWO). The results clearly demonstrated the proposed WOA algorithm giving more than 99.6% efficiency with high tracking speed and minimum payback period under PSC.

Keywords Maximum power point tracking, Photovoltaic, Partial shading conditions, Whale optimization algorithm.

1. Introduction

The demand for energy in all over the world is drastically increasing due to economy rise and improving living standards. Among the conventional energy sources, most of energy is represented by fossil fuels, namely, coal, natural gas and oil. These conventional sources cause environmental pollution and global warming. Renewable energy (RE) resources like hydro, solar and wind are most useful due to the numerous advantages of environmental friendly nature and pollution free. Among REs, solar energy requires low maintenance due to the absence of moving parts, single stage energy conversion, clean and free energy resource. These results of solar energy take many different research approaches are develped in order to get maximum power from PV system [1-5]. Generally solar PV cell is made of a semiconductor material. PV array is developed by connecting more cells in series – parallel (SP), bridge linked (BL) and total cross ties (TCT) [6].

However, the drawback of solar panel is low conversion efficiency due to its dependence on climatic changes. The level of solar extracted power is mainly depence on irraiation. Hence, MPPT techniques are employed for tracking the actual peak power from the solar panel [7-8]. Literature shows wide use of many conventional MPPPT methods classified into i) conventional methods ii) swarm optimization methods and iii) bio inspired based methods. In conventional methods the step size is fixed for the purpose of reducing the power due to the presence of oscillation around MPP. Perturb and observation (PO), hill climbing (HC) and incremental conductance (INC) are some of conventional algorithms [9-10]. The merits of conventional MPPT approaches are easy in implementation and less complexity. However, conventional methods have some demerits. The main disadvantage of P&O, HC and INC is oscillations around MPP, the results leading to power loss. These methods are not suitable for tracking MPP under PSC [11].

Swarm optimization algorithms are suggested for overcoming the inability of the conventional methods to track actual peak power from solar panel under PSC. Some of swarm optimization algorithms are particle swarm optimization (PSO) [12], differential evolutionary (DE) [13], ant colony optimization (ACO) [14] and simulated annealing (SA) [15]. Some of the hybrid algorithms recently developed and appied to the solar PV system. These swarm optimization algorithms have a good capability of nonlinear problems and to track global MPP compared to the conventional methods. The small drawback of these methods is premature convergence that means possibility of tracking local peak. A new bio inspired WOA algorithm proposed in this paper can help overcoming this inability to track problems. The advantages of the algorithm include dealing with nonlinear problem, tracking global peak in PSC, improved convergence speed, flexibility and less complicity. This proposed algorithm can be verified as a powerful technique for dealing with the nonlinear optimization problems.

The remaining parts of this paper formulated as follows: Section 2 provides a description of solar PV model design. Section 3, 4 provide a brief explanation of P&O and GWO. A detailed discussion about proposed WOA method is presented in Section 5. Experimental results and comparison of all three methods form the contents of section 6. Section 7 provides the conclusion.

2. Description of Solar PV model

A Solar PV cell is a made of semiconductor material which converts sunlight into electricity directly by means of photovoltaic effect. The equivalent circuit of a single diode model is shown in Fig.1 that shows a photo current with series and parallel resistance [5].

According to Kirchhoff's current law, the output current equation is expressed as,

$$I = I_{ph} - I_D - \frac{V_D}{R_{sh}} \tag{1}$$

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + I_{ph} \cdot R_s}{V_t}\right) - 1\right] - \frac{V + I_{ph} \cdot R_s}{R_{sh}} \tag{2}$$

Where, I_{ph} is the photocurrent, I_D is the diode current, V_D is the diode voltage, R_s is the resistance connected in series, R_{sh} is the parallel resistance, I_0 is the reverse saturation current, V is the output voltage.

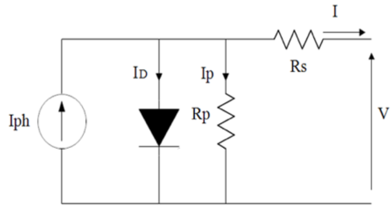


Fig.1. Single diode R_P model

3. Conventional Perturb and Observe method

The P&O method is operated on the basis of periodical perturbations. The first stage of P&O algorithm is to measure the starting PV voltage and current for the measurement of the starting power of PV system. If the difference of measured power is compared with previous power and the resultant is positive, the next perturbation increases in the same direction. In the case of a negative, the next perturbation is a decrease or reversal in the direction. The perturbation size in voltage (ΔV) or duty cycle (ΔD) is very small. The entire step is repeated periodically till the maximum power is observed from the solar PV system [9]. The main drawback of this algorithm is the oscillations presented around MPP. The specification of ELDORA 250 poly crystalline solar PV module is shown in Table. 1.

Table 1. The specification of ELDORA-250W poly crystalline solar PV module

Electrical characteristic of solar panel at STC	From datasheet I-V curve
Voltage at open circuit(V_{oc}), [V]	37.80
Current at short circuit (I_{sc}), [A]	8.80
Voltage at maximum power (V_{mpp}), [V]	30.60
Current at maximum power (I_{mpp}), [A]	8.20
Maximum power(P_m), [W]	250
Temperature co efficient of V_{oc}, $\%/_K$	-0.32
Temperature co efficient of I_{sc}, $\%/_K$	0.42
No. of cells connected in series (n_s)	60

4. Conventional Grey Wolf Optimization

The GWO method has been proposed by Mirjalili and followed by the hunting mechanism of the animal behaviour in nature. For simulating the leadership hierarchy, four different types of grey wolves are considered namely, alpha (α), beta (β), delta (δ), and omega (ω). Here alpha (α) is the fittest function. Both beta (β) are delta (δ) are the second and the third best solutions. The other solutions are assigned to be omega (ω). Hunting, chasing and tracking prey, encircling prey and attacking prey are the important steps involved in designing GWO for optimization of problems. In this algorithm three important steps namely, hunting, chasing and attacking processes are involved in finding the maximum available prey in a region. Mathematical descriptions are expressed as follows,

$$C = |B.\ x\ (r) - x\ (r)| \qquad (3)$$

$$X\ (r+1) = x\ (r) - D*C \qquad (4)$$

Where, B, C and D are represents the coefficient vectors, x (r) represents the position vector of rth iteration of prey, X represents the position vector of wolf. In the hunting mechanism, the alpha components are leaders. Beta and delta are the contributors for hunting prey followed by omega as the caring component which takes care of the wounded grey wolf.

5. Proposed Whale Optimization Algorithm

This proposed WOA is developed based on hunting behaviour of humpback whale for tracking actual peak power presented in solar PV panel at any conditions. The flowchart for proposed WOA algorithm is shown in Fig.2. The steps involved in WOA are briefly explained as follows.
The objective function is represented by

$$F\ (\text{objective}) = \text{maximize}\ P\ (d) \qquad (5)$$

$$P\ (d) = V\ (d) * I\ (d) \qquad (6)$$

Where, P (d), V (d) and I (d) are actual power, voltage and current of PV panel with respect of duty cycle. The range of duty cycle is represented as $0 \leq d \leq 1$. The WOA has three processes. First one is searching for prey, second is encircling process and third is bubble-net attack process.

5.1 *Searching for prey process*

This process is used for searching the maximum available food in the given region. In MPPT, this step is opted for finding the maximum available power from solar the PV panel based on random coefficient vector (C). When $|C| > 1$, the searching process starts in the entire region

$$d_{jk}\ (r+1) = d_{random} - C * D_{jk} \qquad (7)$$

Where, d_{random} is random value of duty cycle, d_{jk} (r+1) is r+1th iteration duty cycle, D_{jk} is vector of kth whale and jth agent.

5.2 *Encircling the prey process*

In this process, the humpback whales employed to encircle the prey. During the encircling process, the contributed whales are updated with respect of the global position. This process takes place during $|C| < 1$ condition. The mathematical expressions are described as follows,

$$D_{jk} = |A * d_{best}\ (r) - d_{jk}\ (r)| \qquad (8)$$

$$d_{jk}\ (r+1) = |d_{best} - D_{jk}\ (r)| \qquad (9)$$

Where, d_{best} (r) is the best duty cycle for rth iteration.

5.3 *Bubble net attack process*

In this process, the speed of humpback whale is classified into two types. The first aspect is linear motion and second is the circular motion. Both methods have 50% probability with each other. The mathematical expression is described as follows,

$$d_{jk}\ (r+1) = \begin{cases} d_{best}\ (r) - C * D_{jk} & \text{if } Rc < 0.5 \\ D'_{jk} * e^{mL} * \cos(2\pi L) + d_{best}\ (r) & \text{if } Rc \geq 0.5 \end{cases} \qquad (10)$$

Where, b is the boundary constant, L is the random number between -1 to +1, Rc also random number and D'_{jk} is the updated coefficient vector.

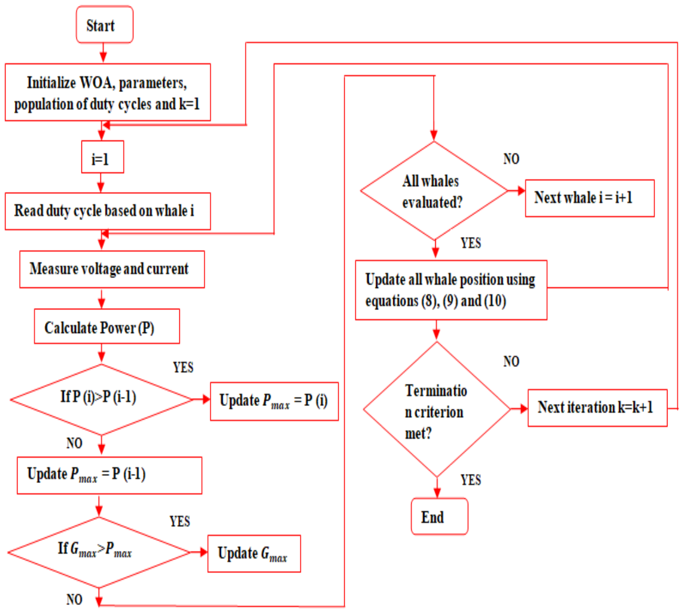


Fig.2. Flowchart for proposed WOA algorithm

6. The discussion of proposed results with conventional methods

Four PV modules are connected in series for the analysis of different shading conditions. This is divided into two types of shading conditions, the first aspect is the normal condition which means uniform shading and the second one is non-uniform shading condition which means partial shading condition. The partial shading exhibited in the panel is due to the passage of clouds, shadows of tall buildings and bird droppings. Figure 4 is the schematic diagram of four PV models connected in series. It depicts both normal and partial shading conditions.

In normal condition, there is no need for a bypass diode due to the same irradiation passing through the entire PV panel but, the PV panel has a bypass diode due to partial shading condition and different irradiations passing on PV panel. It develops a hotspot on the PV panel and the power of PV panel is reduced. Under normal condition, PV panel P-V and I-V curve exhibit only one peak but, in shading condition, many peaks are made as shown in Fig 5. The combination of series-parallel PV patterns is created with normal and shading conditions as shown in Fig 6. P-V and I-V curve of PV panel is shown in Fig 7.

The main drawbacks of P&O algorithm are trapped local peak instead of global peak. Hence, in this paper a novel WOA is proposed for tracking GMPP under strong shading conditions and tested with different shading approaches. P&O, GWO and WOA algorithms are coded and implemented in the MATLAB version 2018 with 1TB Memory, 8GB RAM and Intel core i3 process. Block diagram of PV with boost converter circuit diagram shown in Fig 3. The proposed simulink model is shown in Fig 7(a).

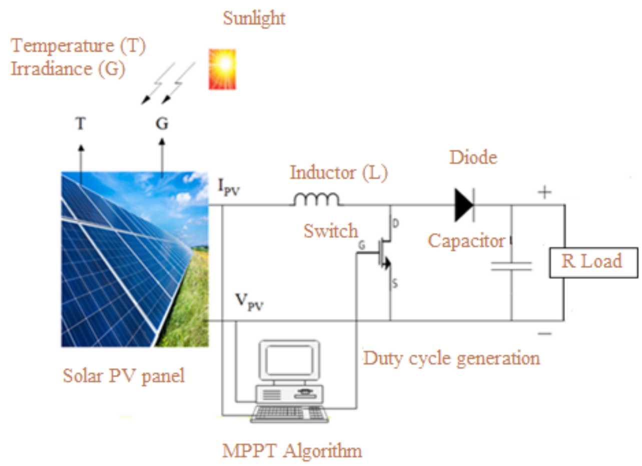


Fig.3. Block diagram of PV with boost converter circuit

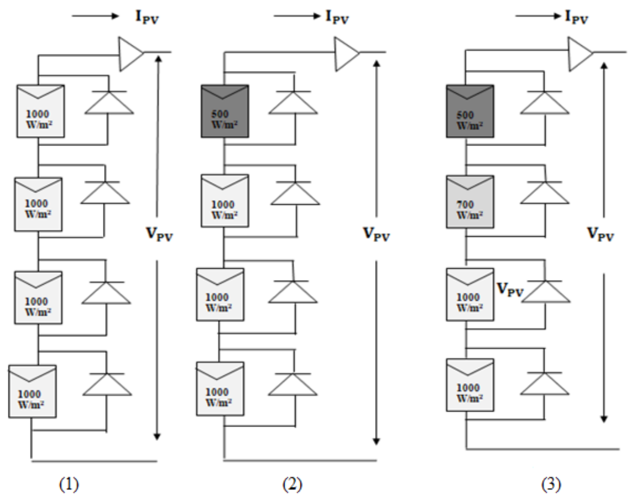


Fig.4. Series PV patterns 1) uniform shading condition, 2) and 3) non-uniform or shading condition.

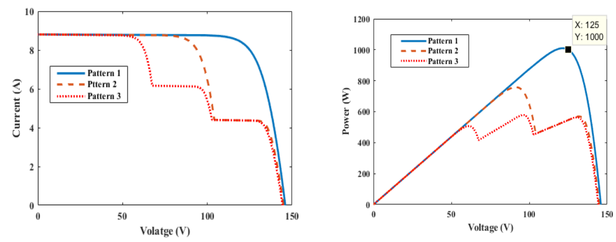


Fig.5. I-V and P-V curve for both uniform and non-uniform conditions for Fig 4.

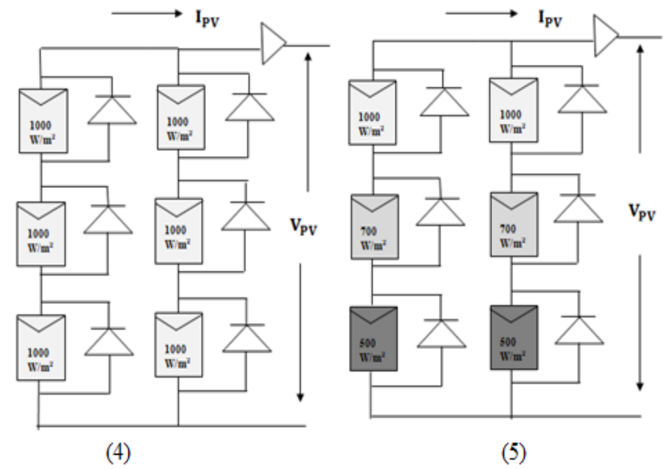


Fig.6. Series – Parallel PV patterns 4) uniform shading condition and 5) non-uniform condition.

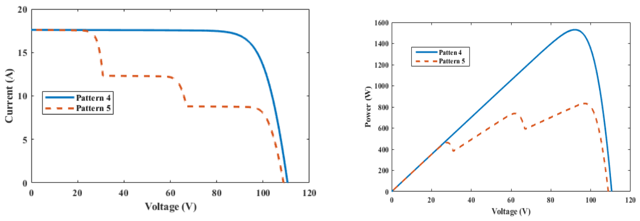


Fig.7. I-V and P-V curve for both uniform and non-uniform conditions for Fig.6.

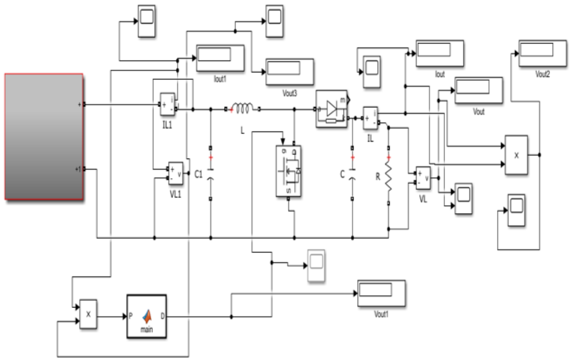
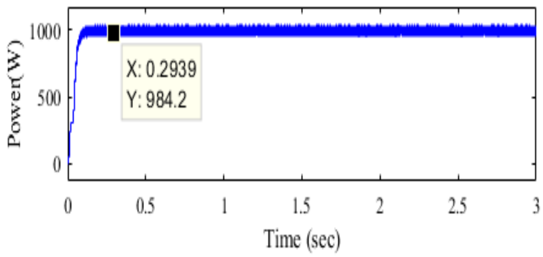


Fig.7(a). Proposed simulink model

In pattern (1) condition, four PV modules are interconnected in series having the same irradiance. So, the P-V curve has only one peak as shown in Fig 5. The global peak is located in 1000W. The proposed WOA tracks GMPP 999W within 0.2 sec with eliminated oscillations at an attractive efficiency of 99.9%. Conventional P&O algorithm achieves 984.2W in 0.293sec. Similarly the GWO obtained is 996.6W with 0.299 sec. The efficiency of P&O is 98.4% and that of GWO is 99.6%. Power curve of a) P&O, b) GWO and c) WOA for pattern (1) is shown in Fig 8.



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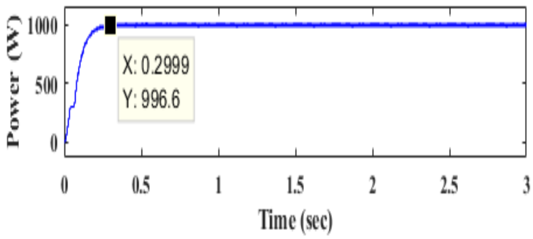

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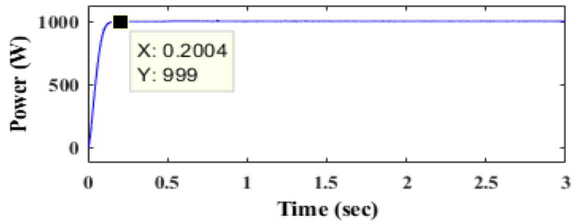
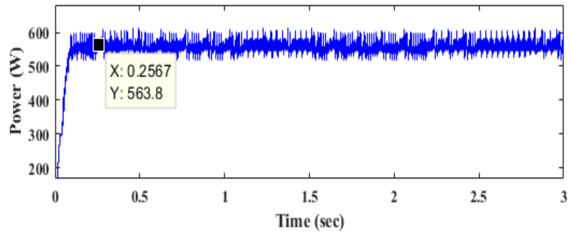


(c)

Fig.8. Power curve of a) P&O, b) GWO and c) WOA for pattern (1)

In pattern (2) condition, four PV modules are connected in series with two different irradiance levels. So, the P-V curve has one global peak and one local peak shown in Fig 5. The global peak is located in 769.95W and local peak in 568.8W. The proposed WOA is executes and tracks GMPP 767.8W within 0.18 sec with diminished oscillations with 99.7% efficiency. The conventional method P&O achieves 563.8W in 0.25sec. Similarly the GWO obtained is 763.4W in 0.25 sec. The efficiency of P&O is 73.2% and that of GWO is 99.1%. Power curves of a) P&O, b) GWO and c) WOA for pattern (2) is shown in Fig 9.



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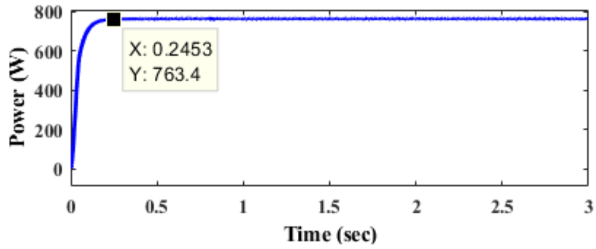

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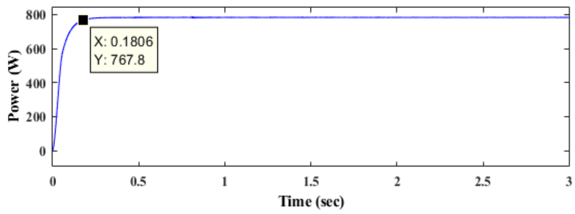
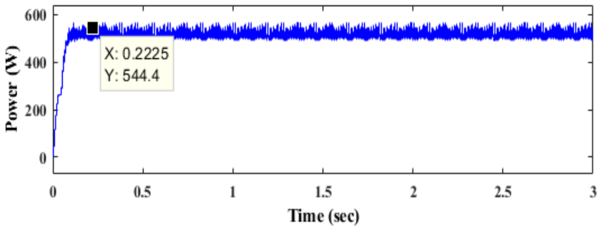


(c)

Fig. 9. Power curve of a) P&O, b) GWO and c) WOA for pattern (2)

In pattern (3) condition, four PV modules are interconnected in series with three different irradiance levels. So, the P-V curve has one global peak and two local peaks as shown in Fig 5. The global peak is located in 600.35W and local peaks in 544.32W and 568.8W respectively. The WOA is introduced and attractively tracked in GMPP 598.1W within 0.13 sec with fewer oscillations with 99.6% efficiency. The conventional method P&O achieves 544.4W in 0.22sec. Similarly the GWO is obtained 577.7W with 0.16 sec. The efficiency of P&O is 90.6% and that of GWO is 96.2%. Power curves of a) P&O, b) GWO and c) WOA for pattern (3) is shown in Fig 10.



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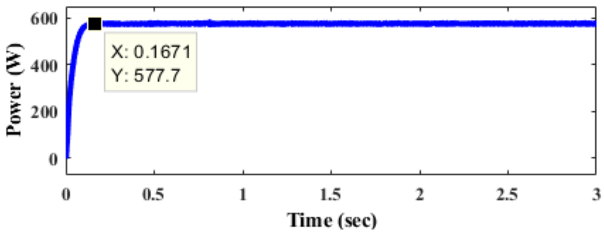
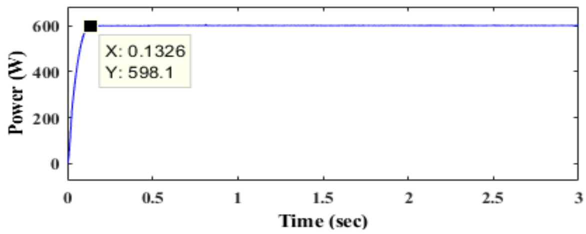


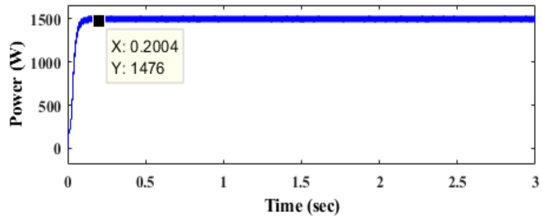
(b)



(c)

Fig.10. Power curve of a) P&O, b) GWO and c) WOA for pattern (3)

In pattern (4) condition, three PV modules are connected in series and two parallel namely, with same irradiance levels. So, the P-V curve has one global peak as discussed earlier and shown in Fig 7. The global peak is located in 1500W. The WOA is executes and tracks GMPP 1499W in 0.09 sec with reduced oscillations with 99.9% efficiency. The conventional method P&O tracks 1476W in 0.20sec Similarly the GWO obtained is 1496W in 0.10 sec. The efficiency of P&O is 98.4% and that of GWO is 99.7%. Power curves of a) P&O, b) GWO and c) WOA for pattern (4) are shown in Fig 11.



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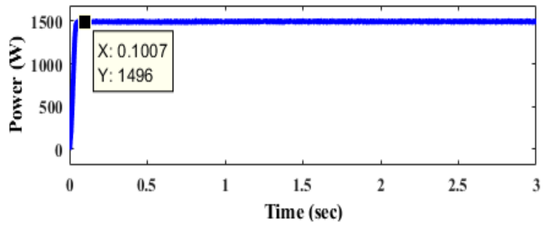

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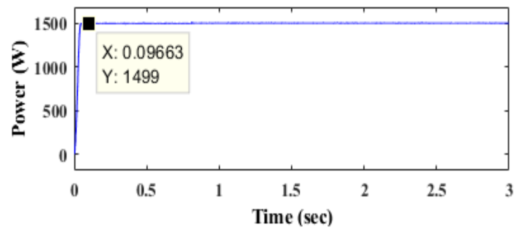
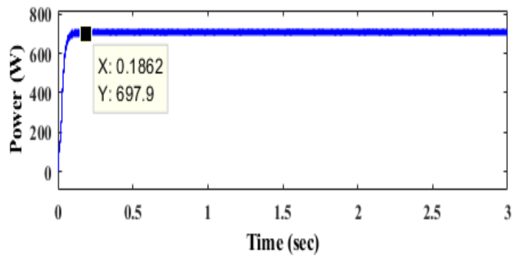


(c)

Fig.11. Power curve of a) P&O, b) GWO and c) WOA for pattern (4)



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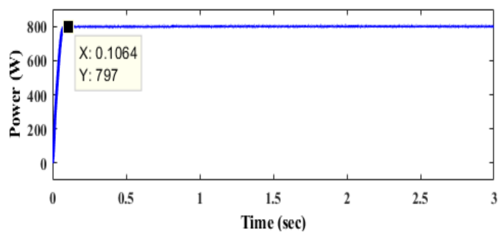

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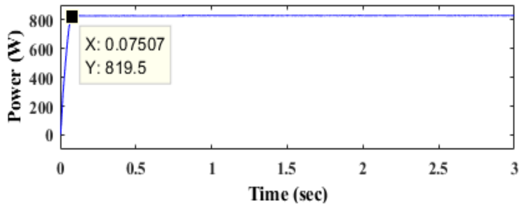

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(c)

Fig.12. Power curve of a) P&O, b) GWO and c) WOA for pattern (5)

In pattern (5) condition, three PV modules are interconnected in series and two parallel with three different irradiance levels. So, the P-V curve has one global peak and two local peaks as shown in Fig 8. The global peak is located in 821.24W and local peaks in 420.2W and 701.8W respectively. The proposed WOA is executes and tracks GMPP 819.5W in 0.07 sec with diminished oscillations with 99.7% efficiency. The conventional method P&O achieves 697.9W in 0.18sec. Similarly the GWO obtained is 797W in 0.10sec. The efficiency of P&O is 84.9% and that of GWO is 97.0%. Power curves of a) P&O, b) GWO and c) WOA for pattern (5) are shown in Fig 12. Details of performance analysis of the proposed MPPT technique with different MPPT techniques under normal as well partial shading conditions are provided in Table 2.

Table 2. Performance analysis of different MPPT techniques with WOA under normal and shading conditions

PV pattern	MPPT technique	Actual power (W)	Obtained maximum power (W)	Efficiency (%)	Tracking speed (sec)	Total energy (Wh) (10hrs)	Cost/month (Rs/month) Rs. 4/unit	Payback (months)
Pattern (1)	P&O		984.2	98.4	0.293	9842	1181.04	42.3
	GWO	1000	996.6	99.6	0.299	9966	1195.92	41.8
	WOA		999	99.9	0.20	9990	1198.8	41.7
Pattern (2)	P&O		563.8	73.2	0.25	7320	878.4	56.9
	GWO	769.95	763.4	99.1	0.24	7634	916.08	54.5
	WOA		767.8	99.7	0.18	7678	921.36	54.2
Pattern (3)	P&O		544.4	90.6	0.22	5444	653.28	76.5
	GWO	600.35	577.7	96.2	0.16	5777	693.24	72.1
	WOA		598.1	99.6	0.13	5981	717.72	69.6
Pattern (4)	P&O		1476	98.4	0.20	14760	1771.2	42.3
	GWO	1500	1496	99.7	0.1	14960	1795.2	41.7
	WOA		1499	99.9	0.09	14990	1798.8	41.6

The installed PV model of ELDORA-250W cost was around Rs.12,500/-. For experimental analysis four PV modules were taken and connected in series which cost was Rs.50,000/-. Table 2 shows the payback period of PV panel using P&O as 76.5 months under strong shading condition in pattern (3), whereas the GWO was achieved in 72.1 months. The proposed algorithm helped achievement of this payback time within three months compared to GWO and within 7 months compared to P&O method.

The performance of the proposed technique is compared with other existing methods which is considering of different parameters involved in MPPT tacking process and tabulated in Table 2. The important parameters in extraction of GMPP process are efficiency, tracking speed, accuracy and playback period. As per the above discussion, the notable merits of the proposed technique are effective tracking of MPP under PSC, robustness and reliability, simplicity in implementation and fast convergence without oscillations.

7. Conclusion

In this article, a new Whale Optimization Algorithm has been introduced for tracking actual peak power from solar PV system under normal and partial shading conditions. Application of WOA to PV the MPP tracking has been successfully tested irrespective of different shading conditions. The convergence speed has been improved and oscillations were reduced steady state and dynamic around MPP by using the proposed technique. In addition, different PV patterns were created and tested with various climatic conditions that demonstrate the WOA as very effective and superiority for all the environmental conditions. The proposed MPPT technique has the ability to replace of other conventional methods. The obtained simulation results have been clearly demonstrated that the proposed WOA algorithm provided more than 99.6% efficiency under PSC with high tracking speed and minimum payback period.

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