An Intelligent Differential Evolution based Maximum Power Point Tracking (MPPT) Technique for Partially Shaded Photo Voltaic (PV) Array

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Abstract

The main aim of this study is to amend the maximum power point tracking (MPPT) for the photo voltaic (PV) array when it suffers from partially shaded conditions. When a photo voltaic panel is shaded for a fraction of time, the power output reduces invariably. During partially shaded conditions the power-voltage curves exhibit multiple maxima which makes the conventional MPPT techniques (perturb and observe, incremental conductance etc.) to get trapped in the local maxima. This paper proposes a Differential Evolution (DE) curdled algorithm to track the global maximum power point thereby increasing the performance of PV array and acquiring a better maxima point. The proposed algorithm is realized in MATLAB/Simulink environment. The credibility of the algorithm is ensured by comparing the results of DE algorithm with its well entrenched counterparts Particle Swarm Optimisation (PSO) MPPT technique and Ant Colony Algorithm (ACO). Also this study proves that the suggested technique would prevail over the most prominent Perturb and Observe (P&O) MPPT when the PV array is under shading conditions.

Keywords: *Differential Evolution Algorithm (DEA); Maximum Power Point Tracking (MPPT); Photovoltaic (PV) array; Partially Shaded Conditions (PSC). Insolation*

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1   Introduction

Photovoltaic (PV) power generators convert the energy of solar radiation directly to electrical energy [1]. With a spurt in the use of non-conventional energy sources, PV installations are being increasingly employed in several applications [2]. However, a major challenge in using a PV source is to tackle the situations like unstable atmospheric conditions and rapidly fluctuating shadow [3]. The performance of a photovoltaic (PV) array strongly depends on the operating environmental conditions, such as temperature, solar insolation, shading and array configuration. Often the PV arrays get shadowed (almost in all applications, except the satellite power systems) completely or partially by the passing clouds, buildings, poles, trees etc. Maximum Power Point Tracking Technique (MPPT) is a mundane and established algorithm, which is being employed in every renewable energy systems. Many research papers have been archived with various schemes over past decades for the MPPT in PV system without considering the partial shading [4]-[7]. The power-voltage characteristic curve of PV array under partially shaded condition has multiple local maxima and causes the mere failure of conventional MPPT or reduces its effectiveness due to their inability to discriminate between the local and global peak [8]. A stage has been reached, where MPPT algorithms with inherent property of tracking at shadings are indispensable. Undoubtedly, a host of algorithm to tackle the shading has been reported. A large number of papers on minimizing the shading losses have been evidenced. The fundamental concept of loss reduction is reconfiguring the hardware connection of photovoltaic modules so that all series modules are provided with a uniform irradiation level [9]. But at times the reconfiguration technique becomes cumbersome when shading pattern changes very rapidly and therefore the research on global search algorithm proliferated and many research papers addressing it have been archived [10].

The numerical analysis highlights the effect of bypass diodes. A MATLAB-based modeling and simulation scheme has been developed for the suitable study of the I–V and P–V characteristics of a PV array under a non-uniform insolation due to partial shading. The mathematical model of partially shaded array helped a lot in developing and evaluating new MPPT techniques for partially shaded conditions [11-12]. PSO has its strong hold on MPPT arena as researchers have well explored the nuances of the algorithm and making it more compatible and efficient by adjusting convergence speed, improving search techniques etc [13-16].A very recent research article on cuckoo search aided MPPT authenticates the fervent interest prevailing in the research arena on this subject [17]. Ant Colony algorithm(ACO),the one which is more conducive for travelling salesmen problem had also its hand in contributing towards maximum power extraction in shaded PV array [18] .Differential Evolution algorithm is the next prominent

global search algorithm to PSO, renders it contribution to make MPPT a intelligent one[19-20].A neoteric research article by Kok Soon Tey[21] elaborates the DE aided MPPT for a partially shaded PV array. This contemporary work uses PSIM software to study the effects of partially shading and claims that the suggested technique has an edge over improved perturb and observe [22] and direct search algorithm [23].

The proposed work in this paper has its own distinctive methodology in implementing DE for partially shaded PV array .Most of the papers including [21] follow a single stage control in which the duty cycle is directly fetched as output from the DE controller whereas the work proposed here in this paper has a double stage control to increase the reliability. The target vectors initialized are the voltage values and not the duty cycle .DE MPPT controller gives a reference voltage at which the peak power exists. This reference voltage is tuned through a PI controller and appropriate duty cycle is generated through pulse width modulation (PWM).Also the detail on the fitness or objective function by which the DE algorithm works is given in this paper whereas in most of the research article pertaining to global MPP tracking does not have detail on that. Moreover the DE MPPT results are compared not only with conventional P&O technique but also with advanced techniques like PSO and ACO.

From the literature survey, it may be concluded that, it is very important to study the P-V characteristics of PV array with the effects of shading, also a suitable probabilistic, stochastic optimization technique which will prevail over conventional algorithms in obtaining the global optima is crucially need. The first objective of this paper is to present a MATLAB-based modeling and simulation scheme suitable for studying the I–V and P–V characteristics of a PV array under the partial shading and section 2 presents this clearly. Secondly, it proposes a Differential Evolution (DE) based modified MPPT scheme to successfully track the maximum power point under shading condition and the versatility of the DE MPPT is checked by comparing its performance with PSO , ACO and Perturb and Observe algorithm, section 3 and 4 witness it .

2   PV Array Modeling

A solar cell is the fundamental component in a solar module. Since the net output voltage of a Solar cell is very low, they are connected in parallel or series or both ways, to meet practical demands. To mathematically model PV array ,the fundamental equations are derived from the equivalent circuit of the solar cell shown in Fig 1.

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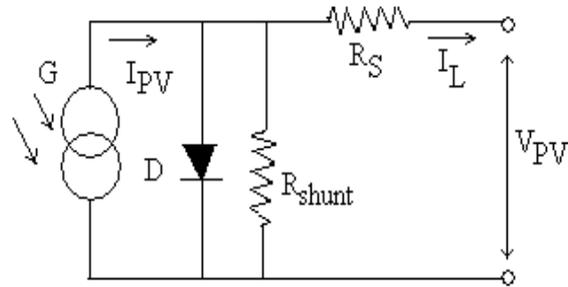
Fig. 1. Equivalent circuit of the practical PV cell

The simplest equivalent circuit of a solar cell is a current source in parallel with a diode. Say I, be the current flowing out of the parallel circuit comprising a current source and diode and it is given by the equation (1)

$$I = I_{pv} - I_d \tag{1}$$
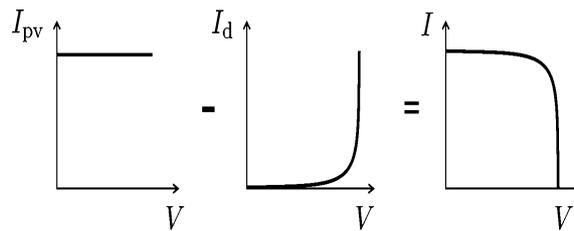
Fig. 2. I-V Characteristic curve of a cell

To simulate the characteristics of the PV panel a detailed mathematical modeling of the same should be done. In this paper, a model of moderate complexity is used. The net current of the cell is the difference of the photocurrent, I_{PV} and the normal diode current I_d:

$$I = I_{pv} - I_0 \left(e^{\frac{q(V + IR_S)}{nKT}} - 1 \right) \tag{2}$$

The model includes the temperature dependence of photocurrent I_{pv} and saturation current of the diode I_o.

$$I_{pv} = I_{pv}(T_1) + K_0(T - T_1) \tag{3}$$

Photon generated current:

$$I_{pv}(T_1) = I_{SC}(T_{1,nom}) \frac{G}{G_{nom}} \tag{4}$$

Increase in I_{sc} for unit increase in temperature:

$$K_0 = \frac{I_{SC}(T_2) - I_{SC}(T_1)}{(T_2 - T_1)} \tag{5}$$

Diode Saturation Current at a given temperature

$$I_0 = I_0(T_1) \times \left(\frac{T}{T_1}\right)^{\frac{3}{n}} e^{\frac{qV_0(T_1)}{nk\left(\frac{1}{T}-\frac{1}{T_1}\right)}} \tag{6}$$

Diode Saturation Current at standard temperature

$$I_0(T_1) = \frac{I_{SC}(T_1)}{\left(e^{\frac{qVoc(T_1)}{nkT_1}} - 1\right)} \tag{7}$$

From equations 4 & 6 it can be inferred that the short circuit current of a PV panel depends upon the irradiation and the open circuit voltage depends upon the temperature. This vital relation can be represented graphically by Fig 3.As the temperature increases the open circuit voltage decreases and also the peak power increases for corresponding increase in insolation
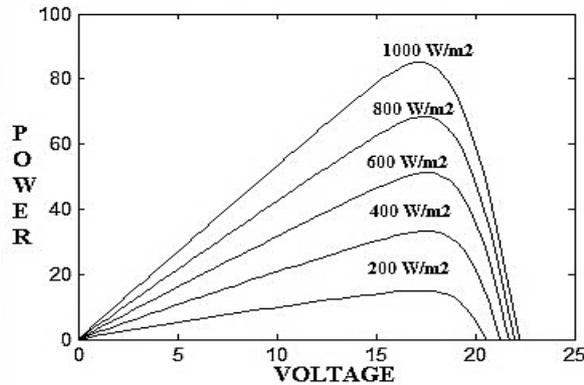
Fig. 3. Different P-V curves under various insolation & temperature.

From the characteristic curves the inferences made are (i) Power of the module has a single maximum point for each irradiation level; (ii) Peak power of the module changes with change in temperature; (iii) Peak of the module changes with the change in irradiation levels; (iv) There is a definite need to track the peak power in order to maximize the utilizations of the solar module.
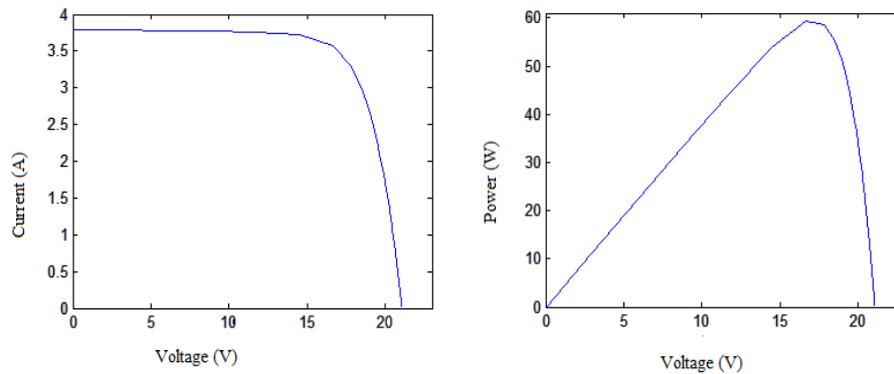
Fig.4. Simulink model of I-V& P-V characteristics

2.1   Effects of the PV Array under Partially Shaded Conditions

When the solar irradiance on a PV array is uniform, only one MPP will exist on the P-V curve of PV array. However, when the irradiance is not uniform (partially shaded) because of many reasons like shadow, sand particles over the panel etc, multiple maximum power points (multiple local maxima) can be witnessed.
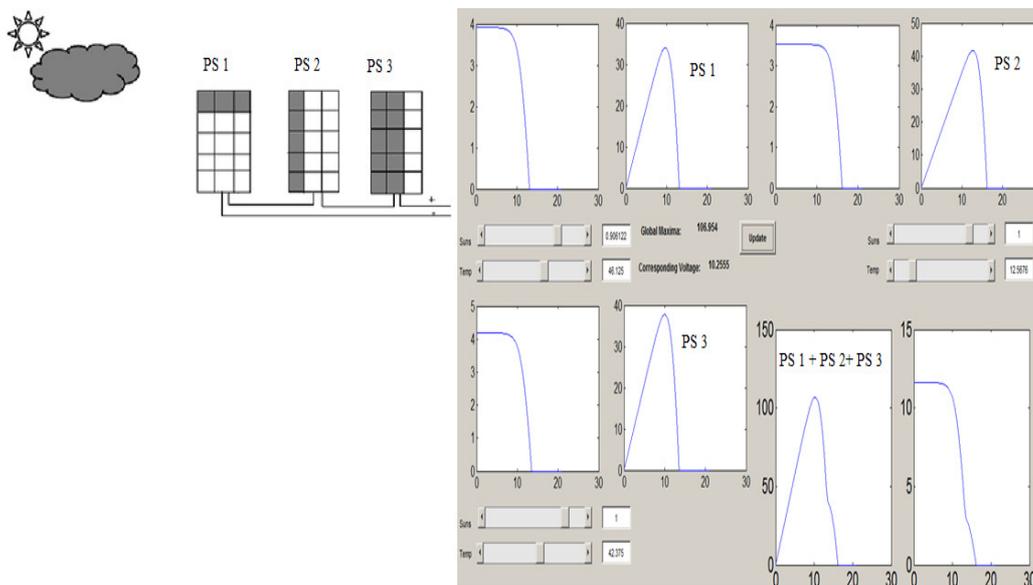
Fig. 5. Simulink model of I-V& P-V characteristics of Partially Shaded PV array

Partial shading of even one cell on a solar panel will reduce its power output. Because all cells are connected in a series string, the weakest cell will bring the others down to its reduced power level. When the panel is partially shaded there is possibility of existence of multi peaks. In a simulation environment, multi peak curves can be witnessed when the panels are exposed to heterogeneous irradiation

and temperature levels .Fig 5 shows three shaded panels which are realized in MATLAB environment through a graphical user interface (GUI) tool and the figure clearly depicts that in a PV array when the individual panels are at partial shaded condition (PS1 ,PS2 PS3) ,the resultant curve (PS1 + PS2 + PS3) exhibit multi power peaks .A typical 3-D diagram having multi peaks is shown in Figure 6.
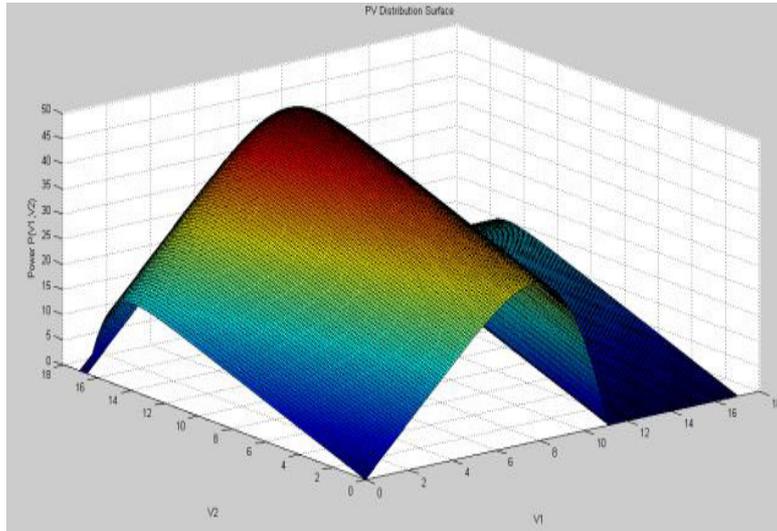
Fig. 6. Three dimensional representation of P-V curve

3   DE Aided MPPT –The Proposed Approach

A block diagram of the proposed system is shown in fig 7. A boost-type dc-dc converter is used to interface the PV module to the load. The MPPT controller is employed to track the maximum power point of the PV array**.** For A uniformly illuminated condition the P&O MPPT algorithm is good enough to find out the MPP of the PV module and produces the respective duty cycle for the dc-dc boost converter. But in partially shaded condition since the conventional P&O MPPT algorithm fails by tracking only the local MPP of the PV module, differential evolution algorithm is used to find out the global MPP of PV module[21]. The inputs to the DE controller will be the irradiation (G) and temperature (T) of the cell. A duty cycle relevant to the peak power is calculated and that duty cycle is fed to the dc-dc converter .The DE algorithm perform its search based on the fitness or objective function[24] .The objective functional equation of DE mppt is so cautiously framed by involving all the four relatively dependent parameters namely Voltage(V), Current(I), Irradiation(G), Temperature(T).

The functional fitness equation of the PV array formed by three individual panels are given by the equation (8)

$$fit = I * PVfunc(I_1, Suns_1, T_1) + i_2 PVfunc(I_2, Suns_2, T_2) + i_3 * PVfunc(I_3, Suns_3, T_3)$$

(8)

Here suffixes 1,2, 3 refers to panel 1 , panel 2, panel 3.

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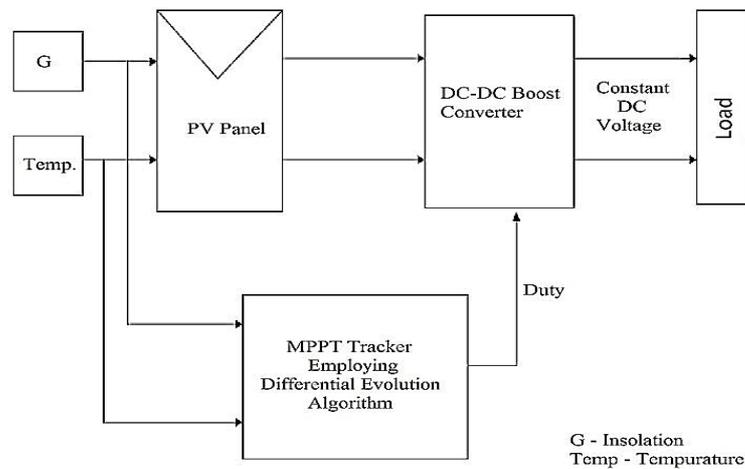
Fig. 7.Proposed Approach

Step 1: Assume,
No. of particles = 5
Scaling Factor F= 0.7
Crossover CR= 0.6
Iter_max =100 err_min = 0.04V
Step 2: Initialize each of the particles with any random voltage V1 volt
Step 3: Calculate the fitness values of all the particles.
Step 4: Select the individual Xi with maximum fitness which is the target vector.
Step 5: Select three more individuals namely Xr1, Xr2, and Xr3 by random
Step 6: Create the trial vector
ViG+1 = Xa,G + F*(Xb,g – Xcg)
Step 7: Create a random vector with values between 0 and 1
Step 8: Compare the values of random vector with crossover constant
Xi'' = Vig+1 if rand(i) <=CR
Xi'' = Xi if rand(i) > CR
Step 9: Calculate the fitness of the resultant vector
Step 10: If the fitness of the resultant vector is greater than the fitness of the target vector, then the resultant vector is selected for the next iteration. Else the target vector is selected for the next generation.
Step 11: Repeat the steps 5 to 10 for the remaining 4 particles
Step 12: Repeat the steps 3 to 11 till the end criteria is met
Step 13: Output the voltage corresponding to the maximum power

4   Results and Discussions

The table 1 shows the electrical parameters of PV system which is taken for the study. A PV array of 3 panels are taken for consideration and the three panels are

not uniformly exposed to sun's irradiation and as a result the cumulative power curve will exhibit a multi peak embedded curve as shown in Fig.8. The simple observation on Fig.8 reveals that there occur global maxima at 82.2 Watts and two local maxima at 64 Watts and 40 watts.

Table 1: Parameter Specifications of WS-140 (WSBYW03101693) Solar panel at Standard test condition (STC)

Parameters	Values
Maximum Power (P_{max})	140 watts
Voltage at P_{max} (V_{mpp})	17 volts
Current at P_{max} (I_{mpp})	8.24 amps
Open circuit voltage (V_{oc})	21 volts
Short circuit current (I_{sc})	8.89 amps
Temperature coefficient of I_{sc} (K_I)	$(0.065 \pm 0.015)\%/$ ^{o}C
Temperature coefficient of V_{oc} (K_V)	$-(80 \pm 10)mV/$ ^{o}C
NOCT	(47 ± 2) ^{o}C
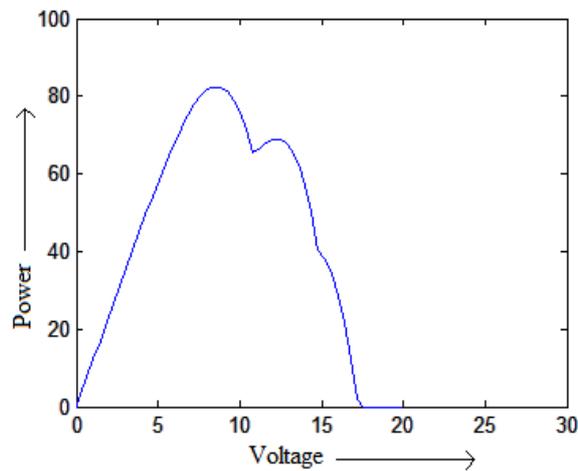
Fig. 8. PV curve of a shaded array

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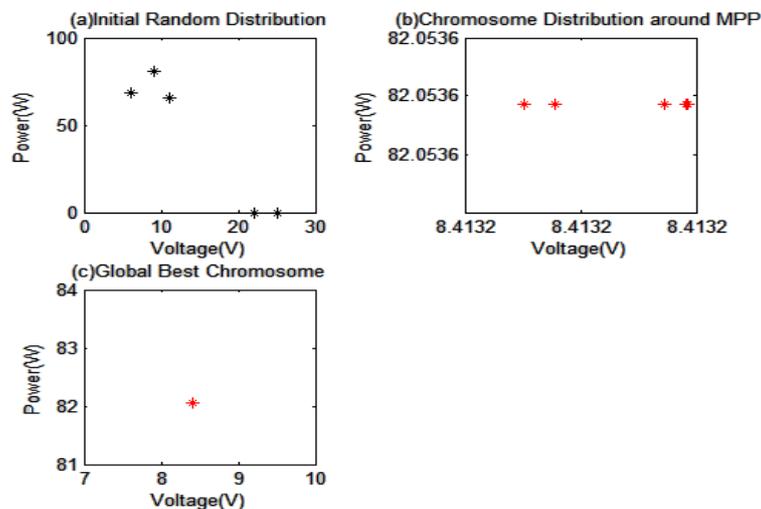
Fig.9. Convergence of DE MPPT (Figure (a) shows the initial distribution chromosomes
(b) Convergence around MPP (c) convergence in MPP

Fig.9. shows the convergence of differential evolution aided MPPT .It has 3 panes where pane(a) shows the random distribution of chromosomes over the search space. One can asses five chromosomes that are distributed randomly. Pane (b) shows the convergence of chromosomes around the maximum power point say approximately around 82W.The final convergence at maximum power point is shown in pane (c).Though the algorithm is made to run for 100 iterations ,the convergence of DE is so versatile that the maximum power is tracked within 15 odd iterations irrespective of any change in temperature or irradiation. Table 2 shows the tabulation between voltage and Power values (G best) and (G fit) with respect to 15 odd iterations.

The power output and the operating voltage waveforms are shown in figure 10. Also the experiment is carried out at three different instants (timings) and the results are shown in 3-D graph(refer figure 11). The inference is that within 10 iterations the DE algorithm swiftly converges though its initial search starts with random initialization. The comparison table presenting various other MPPT techniques are shown in table 3.
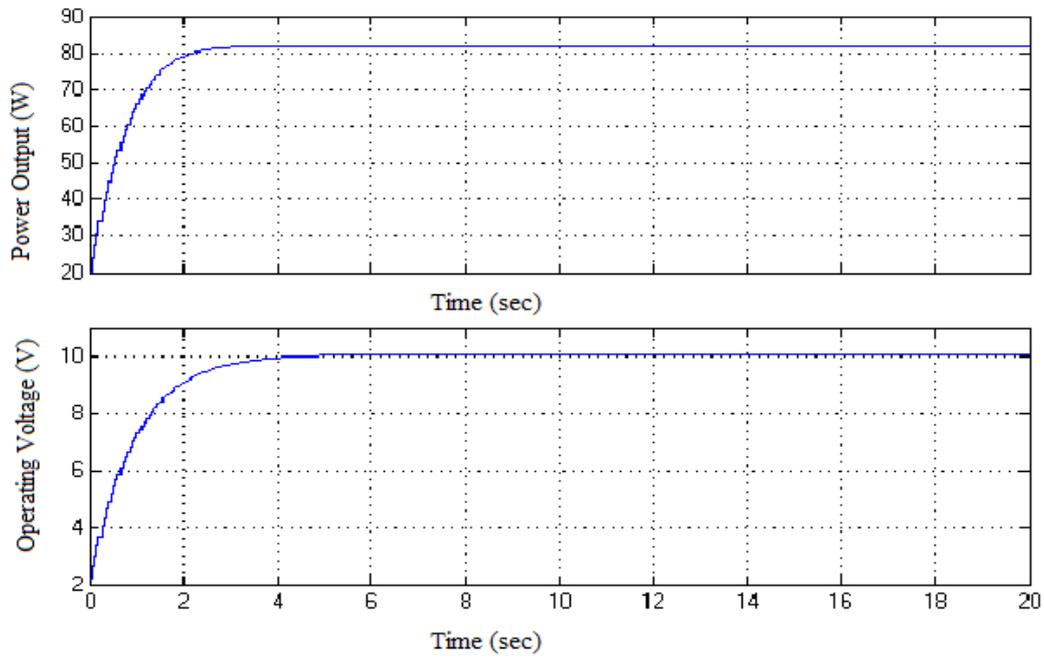
Figure 10 Simulation output of DE MPPT for the shaded array

Table.2 Simulation output of DE MPPT

Iteration	Voltage	Power Output
1	9.4219	79.0708
2	9.4287	79.0708
3	8.8354	81.6079
4	8.3776	82.0499
5	8.4188	82.0535
6	8.4188	82.0535
7	8.4164	82.0535
8	8.4137	82.0536
9	8.4133	82.0536
10	8.4133	82.0536
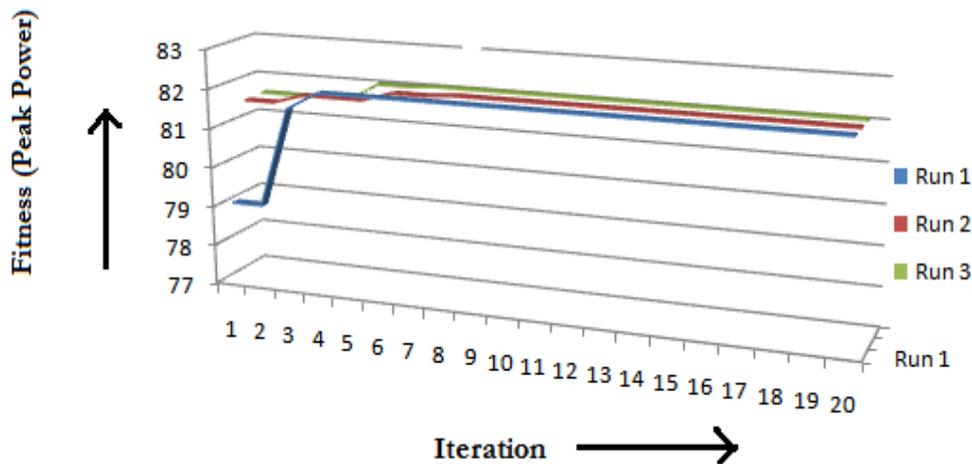
Fig.11 Convergence graphs at 3 instants (runs)

5   Comparative Results of MPPT Techniques

5.1   Perturb & Observe MPPT

The Perturb and Observe (P and O) mppt logic is to adjust the operating voltage of the panel until the maximum power from it is achieved. During this operation the terminal voltage is continuously perturbed and power is measured. In a stipulated direction if power increases for a change in operating voltage then it is understood the search is moving forward towards MPP. If the power decreases, then the operating point would have crossed peak power point and the direction should be reversed. This perturbation is done by controlling the duty cycle (δ).But when multiple peaks occur. Perturb and observe technique when employed to a partially shaded PV array, there is every possibility of this algorithm to get stuck with local maxima instead of tracing the global one .Table 4 presents that, for a given shading pattern the perturb and observe technique gets stuck with the local maxima of 38 Watts .

5.2   Particle Swarm Optimisation

In PSO algorithm, the particles position is changed based on the P_{best} particles in the neighbourhood as well as G_{best} achieved by all the particles. The new particle position is given by the equation

$$x_i^{k+1} = x_i^k + \Phi_i^{k+1} \tag{9}$$

where x_i^k is the particle position and Φ_i is the step size. The velocity is given by

$$\Phi_i^{k+1} = \omega\Phi_i^k + c_1 r_1 \left\{ P_{besti} - x_i^k \right\} + c_2 r_2 \left\{ G_{besti} - x_i^k \right\} \tag{10}$$

The PSO algorithm is the most prominent MPPT technique among all the global search algorithm .Among all other global search algorithm , PSO is the most reliable among research community as many papers have been archived for PSO MPPT .The PSO MPPT is advantageous than any other technique in convergence , versatility and reliability . But at the same time , the proposed DE algorithm has a slender edge over the PSO in Power output value .The power tracked by DE algorithm is slightly more compared to the power obtained by PSO for the same shading pattern ,Table 3 witnesses the same .

5.3   Ant Colony Algorithm

Ant colony algorithm came into existence by mimicking the social behavior of ants. When ants search their food it would follow a shortest path between their nest and food. They have an inherent capacity to emit a chemical called pheromone which drags response within members of the same species .When ants wander for search of food it would emit pheromone trail on their way. The search may be random initially. Ants may also follow the same path while returning to the nest as it would trace the pheromone trail. Therefore the pheromone trail becomes even thicker and rigid and will be the shortest path. If the pheromone path is not the shortest then it would evaporate and vanish off its own.

$$T_{ij} = \rho T_{ij}(t-1) + \Delta T_{ij}; \qquad t = 1,2,3...T \tag{11}$$

where

T_{ij} - Revised concentration of pheromone

ΔT_{ij} - Change in Pheromone concentration

ρ - Pheromone concentration rate (0-1)

The pheromone rate 'ρ' plays a crucial role as absurd values. Concentration rate would wrongly direct the convergence to happen at local maximum.

Pheromone concentration ΔT_{ij} is given by

$$\Delta T_{ij} = \begin{cases} R / fitness_k & I_{ij} \ is\ chosen\ by\ ant\ k \\ 0 \ otherwise \end{cases} \tag{12}$$

ACO MPPT has dragged less attention in the MPPT research arena but for a research initiative [18].This research article claims to have superior characteristics than PSO for the shading pattern . The complexity of realizing the ACO MPPT as hardware still remain unsolved where as the DE algorithm has a clear advantage over its ACO counterpart .The convergence of ACO is slow compared to DE .Table.3 shows the comparative analysis of all three the MPPT techniques discussed in this section with that of DE MPPT .

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Table 3. Comparative results of MPPT Techniques

Shading Pattern	Scheme	Power delivered	Time taken to reach MPP
Panel 1 45*C ,0.8Suns Panel 2 25, 0.6 Panel 3 45,.72	Without MPPT	12.05 W	NA
	With P&O MPPT	38.0 W	0.02s
	DE MPPT Controller	<u>81.79W</u>	2.276s
	PSO MPPT Controller	81.37 W	1.8 sec
	ANT MPPT Controller	81.367	2.2 sec

6   Conclusion

The photovoltaic (PV) industry is grooming into a most reliable energy market among other renewable sources .Research in improving its conversion efficiency is in rigor that the cost of PV system will come down relatively .Maximum power tracking technique which is a indispensable embodiment in a photovoltaic power system which is used to enhance the power conversion efficiency. .DE based mppt algorithm is proposed here for a partially shaded PV array where conventional mppt algorithms tend to fail .The results validate the versatility of the proposed technique and assures that DE algorithm has a clear edge over its counterpart techniques like PSO AND ACO either in convergence technique or maximum power extraction .For a given shading pattern DE mppt is capable of extracting 82.5 Watts where as a conventional perturb and observe mppt technique will get stuck with a local maxima of 42 Watts. The work suggested can be extended for multiple PV arrays with a multi dimensional search by DE algorithm.

7   Future Work

To enhance the power extraction capability, the power conditioning units may be placed for each PV shaded panel in an array .But when multiple power conditioning units are used, a uni-dimensional DE will not be sufficient and the total power extraction capability will be poor. Therefore a multi-dimensional DE should be implemented.
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