International Journal of Engineering

Journal Homepage: www.ije.ir

Optimal Reconfiguration of Solar Photovoltaic Arrays Using a Fast Parallelized Particle Swarm Optimization in Confront of Partial Shading

H. Heidari*[a], M. Tarafdar Hagh[a,b]

[a] *Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran*
[b] *Engineering Faculty, Near East University, North Cyprus, Mersin 10, Turkey*

PAPER INFO

Paper history:
Received 29 May 2019
Received in revised form 1 july 2019
Accepted 05 July 2019

Keywords:
Solar Energy
Electrical Array Reconfiguration
Partial Shading
Photovltaic Arrays

ABSTRACT

Partial shading reduces the power output of solar modules, generates several peak points in P-V and I-V curves and shortens the expected life cycle of inverters and solar panels. Electrical array reconfiguration of PV arrays that is based on changing the electrical connections with switching devices, can be used as a practical solution to prevent such problems. Valuable studies have been performed to justify the electrical array reconfiguration efficiency. However, there are some problems such as algorithms complexity, simulations runtime and the inability of objective functions to detect the best array. In this paper, the photovoltaic (PV) array reconfiguration problem is solved by using a parallelized Particle Swarm Optimization (PSO) algorithm, which searches for reducing the rows current difference. The proposed algorithm is implemented in MATLAB/Simulink and is numerically compared with some related works. Results show the simplicity and higher power outputs of the proposed algorithm compared to published papers while ensuring less simulation runtime. Depending on the shading pattern, the power enhancement is different. The maximum power increase is 26.5 percent of the total array output power.

***doi**: 10.5829/ije.2019.32.08b.14*

1. INTRODUCTION

According to the IEA's renewable 2018 market analysis and forecast report, the penetration of renewable energy in the electricity sector is steadily increasing. In the meantime, solar energy is attracting much attention, arising from generation simplicity and availability of its source, the sun, especially in the remote areas [1]. Also, with the technological advancements of solar cells [2] to reduce the production costs, solar energy penetration is also increasing in power systems. The efficiency of solar cells depends on several environmental factors. Partial shading is one of the problems that decrease the efficiency of solar cells [3] and alters P-V and I-V curves [4]. In partial shading, P-V and I-V curves are exposed to several peak points [5, 6] and subsequently, this can create the problem of identifying the maximum power point for maximum power point tracker units [7]. The most affordable way to deal with power output reduction during partial shading is to equip each module with an inverter and a maximum power point tracker. This solution is not practical due to its huge costs.

Another solution is to change the arrangement of the modules, which is referred to as the array reconfiguration [8]. Solar modules can be connected in series, parallel or a combination of the two. There are various connection configurations for PV arrays that are reported in literature [9]. The purpose of serial and parallel connection of modules is to increase the output voltage and current of the array, respectively. Generally, both current and voltage are considered in the configuration of the modules, especially for large-scale PV plants. In this way, a combination of series and parallel connections is suggested. The two commonly used connection types are Series-Parallel (SP) and Total-Cross-Tied (TCT). In the SP type of connection, the number of modules is

*Corresponding Author Email: Ha.Heidari@tabrizu.ac.ir (H. Heidari)

Please cite this article as: H. Heidari, M. Tarafdar Hagh, Optimal Reconfiguration of Solar Photovoltaic Arrays Using a Fast Parallelized Particle Swarm Optimization in Confront of Partial Shading, International Journal of Engineering (IJE), IJE TRANSACTIONS B: Applications Vol. 32, No. 8, (August 2019) 1177-1185

connected in series. Then the groups of series modules are connected in parallel, while in the second connection type, each module is in series with modules in a column and is parallel with modules in a row. The TCT arrangement is the most commonly used type because it has the lowest mismatched power and highest efficiency in partial shading [10, 11]. Figure 1 shows the described connection types for a 9×9 set. The modules are numbered with subscript 'ij' where 'i' stands for the row and 'j' denotes the column in which the module is connected.

When PV array is exposed with partial shading, rows current varies with each other and this creates multiple peaks in P-V and I-V curves because of bypassed modules for protection. This will increase the mismatched power between the panels and power losses. Generally, there are three solutions for alleviating the effects of partial shading consisting of physical relocation, electrical rewiring, and electrical array reconfiguration. Among such solutions, the electrical array reconfiguration is the most effective method in spite of the complexity [12]. Physical relocation-based algorithms, such as Su Do Ku [13] or competence square method [14] have a drawback of a laborious task. Although, the electrical rewiring-based algorithms introduced by Rao et al. [15] does not have such drawback, they need additional rewiring [12].

Changing the states of connection switches of the modules is expressed as electrical array reconfiguration. Paklak [16] proposed a method for rearranging the

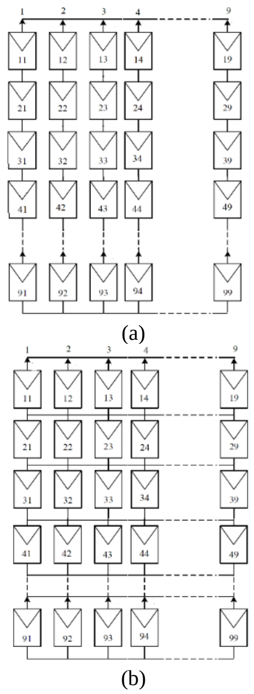


Figure 1. Most commonly used interconnection schemes of PV modules, (a) SP connection, (b) TCT connection

electrical connections of arrays that consist of an adaptive and a static section. It mitigates the effects of partial shading by modifying the adaptive section's switches status by examining all possible modes for the switches. Jazayeri et al. [17], introduced the following electrical array reconfiguration scheme. They have searched for an arrangement of the adaptive section to get the total insolation level of rows close to the average of total insolation on the whole of the array's rows. A full switchable array is more efficient in confront of partial shading because it has more flexibility for connections changing. In addition, as the PV array becomes larger, the volume of calculations increases. For example, there are 9×9! possible switching modes for a 9×9 PV array. In such cases, the problem becomes more complex, and the metaheuristic algorithms are the best candidate for the solution method. Babu et al. [12] and Deshkar et al. [18], solved the problem of optimal electrical array reconfiguration by using particle swarm optimization (PSO) and genetic algorithm, respectively. The process of determining an optimum arrangement is similar in both of these two, but PSO has the advantage of faster convergence in comparison with the genetic algorithm, resulting in less time. However, the objective functions reported in literature [12, 18] included terms that may caused the variables to be trapped in local optimal points and did not reach to the main goal of reconfiguration, maximum power output. Additionally, the problem of time and accuracy of results have always been under discussion for such algorithms. The calculations runtime, especially in larger PV arrays, may be difficult to handle because of the larger range of feasible region and number of variables. The answer lies in computer science. Parallel and distributed computing techniques as parts of this science allow for faster execution [19]. Thus, in this paper, by using MATLAB parallel computing toolbox, a parallelized PSO developed and is applied to the problem of reconfiguration of PV modules to meet the real-time execution needs.

Parallel computing provides clear horizons for real-time computing. In general, parallel computing can be done differently in two widespread-used architectures, Single Instruction-Multiple Data (SIMD) and Multiple Instruction-Multiple Data (MIMD). The performance of these two architectures depends on the volume of the calculations. By observing the works in the context, it is found that the MIMD-based algorithms are more suitable (in terms of population size and iteration numbers) for electrical array reconfiguration problem. Hence in this paper, a parallelized version of PSO on a MIMD-based processor (multi-core CPU) is suggested.

The contributions of this paper are as follows: A new non-constrained optimization formulation is proposed for electrical array reconfiguration of PV modules. The proposed objective function eliminates the possibility of trapping on local optimum points. In addition, in order to increase the speed of computations, a fast parallelized PSO is developed and used as a solution method.

The paper reminder is organized as follows: In section 2, a study is conducted on solar cells utilization with environmental conditions changes. In section 3, the formulation of the optimization problem is presented and then the parallelized PSO is described. In section 4, the simulation results are reported. Finally, in section 5, the paper conclusion is presented.

2. SYSTEM DESCRIPTION

Various equivalent circuits can be used for solar cells modeling. A solar cell equivalent circuit can be an ideal model with the least detail or a dual-diode model with seven parameters that will have the most accuracy in the reviews [20]. In this paper, the single diode model is used for solar cells modeling. The I–V characteristic is formulated as follows [20]:

$$I = I_{PV} - I_{s(}e^{\frac{q(v+R_sI)}{nkT}} - 1) - \frac{(v+R_sI)}{R_p} \tag{1}$$

where R_s and R_p stand for series and parallel resistances in the equivalent circuit, respectively. n is the number of cells in series, q is the charge on an electron, k is the Boltzmann constant, T is the absolute temperature of the cell (Kelvin), I_{PV} is the photoelectric current and I is the current generated by the solar cell. All five parameters of the solar cell are affected by environmental conditions such as insolation level and ambient temperature. Depending on the temperature and insolation level, the photoelectric current changes as follows [20]:

$$I_{PV}(T,G) = I_{sco}(\frac{G}{G_{STC}})(1 + a(T - T_{STC}))(\frac{R_S+R_p}{R_P}) \tag{2}$$

where I_{sco} is the short circuit current, G is the insolation level, a is the temperature coefficient and E_g is the bandwidth energy. The subscript STC stands for the Standard Test Condition (G=1000$\frac{w}{m^2}$, T=273.15+25℃). Assuming the temperature has no volatility, the current of each module changes in proportion to the ratio of insolation to its STC value. Therefore, the current generated by each module can be written as follows [18]:

$$I = kI_n \tag{3}$$

where $k = \frac{G}{G_{STC}}$ and I_n is the generated current of the module in the STC. The current of a row is equal to the total currents of the modules in that row. As mentioned earlier, in partial shading, the power output is reduced. It is noteworthy to mention that the power output reduction is not just because of insolation level reduction, but also because of the inappropriate arrangement of the panels. Therefore, reconfiguration of the panel's connections can alleviate the partial shading effects. To show the efficiency of the proposed algorithm, extensive tests and analysis on a 9×9 PV array with TCT connection are presented. Also for emphasizing the importance of application of parallel processing, runtime results are compared.

3. OPTIMAL RECONFIGURATION OF ELECTRICAL CONNECTIONS

3. 1. Optimization Problem To further explore the proposed methods in the literature, first, their proposed functions are examined. The fitness function is defined as follows [12, 18]:

$$O.F = \max(\sum_{k=1}^{nr} V_k I_k + \frac{W_e}{\sum_{n=1}^{nr}|I_{max} - I_n|} + W_f P_a) \tag{4}$$

where V_k and I_k are the voltage and current limit of each row, I_{max} and I_n stand for the maximum current of the m_{th} row and maximum row current of the m_{th} row when bypassing is considered, respectively, P_a is the output power without bypassing and W_f and W_e are constant values. The first term of Equation (4) is searching for a configuration that the rows current is equal to each other, as much as possible. The aim of the second term of the objective function is to reduce the difference between the current of each row with its maximum value and the third term seeks to increase the output power without bypassing the modules. This goal is, in fact, searching for an array of the modules that maximizes the current of modules. Because the sensitivity of voltage of modules to insolation level is very low, the voltage maintains constant. The afformentiond fixed numbers are empirically determined. Obviously, the sensitivity of the objective function and subsequently the effeciency of reconfiguration results to these numbers is undeniable. Therefore, for simplicity of computations and eliminating the role of the fixed numbers on convergence, the objective function can be assigned to one component, which reduces the difference between the generated current of each row of modules with its maximum value. Thus, in this paper, the objective function is formulated as follows:

$$O.F = \min(\sum_{k=1}^{nr}(I_{max} - I_k)^2) \tag{5}$$

Taking into account Equation (5), all goals in Equation (4) is achieved. In partial shading, because the voltage has a slight change, the array output power is maximum when the rows current is equal to each other. Also, the second term of Equation (4) automatically increases. In addition, the higher the output current of each row, the third part of Equation (4) will automatically increase.

3. 2. Particle Swarm Optimization To solve optimization problem, the particle swarm optimization algorithm inspired by the collective behavior of birds for the first time was proposed in 1995 by Eberhart and Kennedy [21]. This basic PSO in the next years with a wide range of researches has been dramatically expanded to include more accurate results [22]. The typical version of this algorithm with slight modifications from the original version can be described as follows:

The velocity (V_n^i) of each member of the swarm (particle n) is determined by the best position ever to be placed in ($Pbest_n^i$) and the best position of the whole swarm ($Gbest^i$). Then, according to the obtained values, the particle moves toward search space (X_n^{i+1}). The index i indicates the iteration number. With these explanations, the velocity of each particle and its new position in the search space are determined by Equations (6) and (7), respectively.

$$V_n^{i+1} = wV_n^i + c_1r_1\left(Pbest_n^i - X_n^i\right) + c_2r_2\left(Gbest^i - X_n^i\right) \tag{6}$$

$$X_n^{i+1} = V_n^{i+1} + X_n^i \tag{7}$$

where c_1 and c_2 are constant numbers, r_1 and r_2 are random variables that have been limited to the range of [0, 1] and w is the inertia weight.

3. 3. Parallel PSO After the initial parameter setting and population (swarm) generation, the population is divided into some sub-populations. The division of the population is done randomly. Then the main loop of the optimization process, particles movement and fitness evaluation, is completely deposited to the processor cores. After certain iterations and meeting the completion criteria of the loop, the results of each sub-population are brought to the MATLAB work-space. Then by comparing the best results of the sub-populations, the best answer to the problem is chosen. This process is fully illustrated in Figure 2. The proposed algorithm by reducing the sequential steps of the optimization process causes to increase the execution speed.

3. 4. Optimization Constraints Any solution should satisfy the constraint that switching just can be done for unity columns. It is obvious that a constrained optimization restricts the search space and increases the volume of calculations. In this paper, to remove the constraints, a 9×9 matrix of variables is considered that its elements are limited to the range [1, 9]. In each column of this matrix, only non-repetitive integer numbers can be placed. It is noteworthy to mention that the adjacent columns in the variables matrix are non-interdependent. each column of the matrix is compared with numbers 1-9, and the closest non-repetitive number is specified for each element of the column. Therefore the switching constraints are fulfilled in the stage of particles movement and this causes a wider search space with lower computational volume.

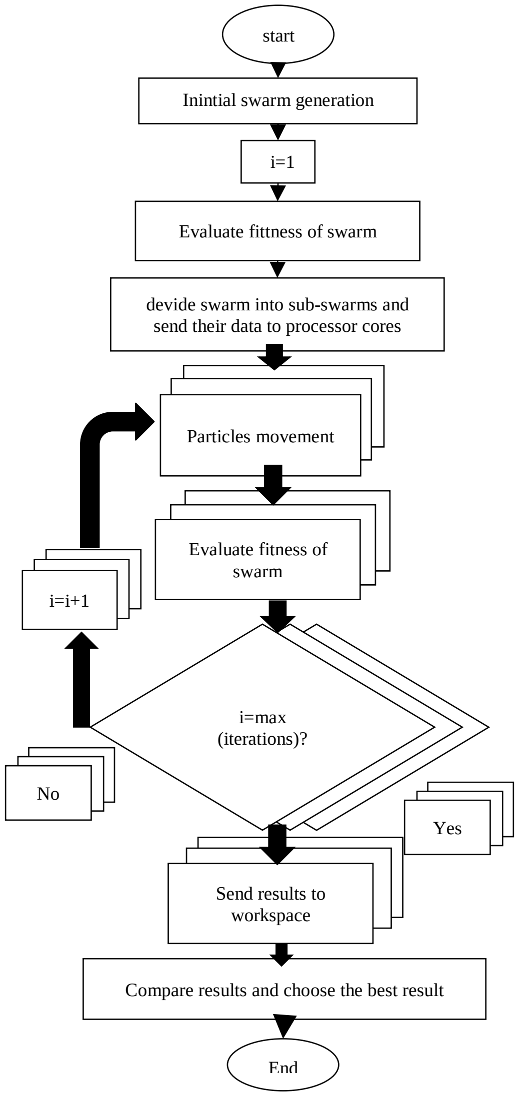


Figure 2. The proposed Parallel PSO

4. SIMULATION RESULTS

In order to examine the efficiency of the proposed algorithm in confront of partial shading, two shading patterns, short-wide and long-narrow, are tested. The reason for choosing these patterns is to provide numerical comparisons of the results with related works. Simulations are performed on a 6700hq CPU with 4 GB memory. PV cells are modeled based on five parameters equivalent circuit in MATLAB/Simulink. The specifications of the solar panels are listed in Table 1. It should be noted that the solar panel specifications given by Babu et al. [12], are not clearly reported. Therefore, in order to avoid misleading conclusions, the reconfiguration results of Babu et al. [12] are repeated once again with new specifications. The PSO parameters are presented in Table 2.

Babu et al. [12] have compared its PSO-based algorithm with a genetic algorithm introduced by Deshkar [18] and Su Do Ku [13]. The results indicated the superiority of the PSO algorithm. Therefore, in this paper, the results are compared with data reported by Babu et al. [12].

TABLE 1. Specifications of solar panels

Open circuit voltage	**Short circuit current**	**Voltage at the maximum power point**	**Current at the maximum power point**	**Number of cells**
22.24 v	4.71 A	18.33 v	4.37 A	36

TABLE 2. PSO parameter setting

Swarm size	c_1	c_2	w	**Maximum iterations**
22.24 v	4.71 A	18.33 v	4.37 A	500

4. 1. Shading Pattern Case The shading pattern on the array is shown in Figure 3. It is assumed that the temperature remains constant and only the panels receive different levels of solar irradiance. As mentioned earlier, the maximum current of a row is the total currents of its panels. For example, the rows 1-9 current are obtained as follows:

$$I_1 = I_2 = I_3 = I_4 = I_5 = 9 \times \frac{900}{1000} I_n$$
$$I_6 = 9 \times \frac{800}{1000} I_n \tag{8}$$
$$I_7 = I_8 = I_9 = 3 \times \frac{600}{1000} I_n + 3 \times \frac{400}{1000} I_n + 3 \times \frac{200}{1000} I_n$$

When the requested current of the load exceeds the maximum current of a row, the row will be bypassed for protection. In this case, the array voltage drops. For example, if the requested current exceeds $3.6I_n$, rows 7, 8 and 9 are bypassed and the array voltage is obtained as follows:

$$V_A = 6V_n + 3V_d \tag{9}$$

where V_d is the diode voltage and can be neglected in comparison with panel voltage (V_n). These calculations are, in fact, the basis for determination of the theorotical maximum power point of the array.

After applying the proposed algorithm, the shading pattern changes to Figure 4 (a). Also, the results repoerted by Babu et al. [12] are represented in Figure 4 (b). The theoretical maximum power points for TCT, [12] and the proposed algorithm are represented in Table 3. From Table 3, it is evident that both Babu et al. [12] findings and the proposed algorithm are able to reach higher maximum power points than TCT configuration. Although the maximum theoretical powers obtained by Babu et al. [12] and the proposed algorithm are equal, the P-V curves comparisons (Figure 5 (a)) show that the proposed algorithm reaches to higher power outputs. Comparing the I-V curves (Figure 5 (b)) reveals the reason. As shown in Figure 5 (b), the proposed algorithm is able to reach to higher currents for equal voltages than

900	900	900	900	900	900	900	900	900	$I_1 = 8.1I_n$
900	900	900	900	900	900	900	900	900	$I_2 = 8.1I_n$
900	900	900	900	900	900	900	900	900	$I_3 = 8.1I_n$
900	900	900	900	900	900	900	900	900	$I_4 = 8.1I_n$
900	900	900	900	900	900	900	900	900	$I_5 = 8.1I_n$
800	800	800	800	800	800	800	800	800	$I_6 = 7.2I_n$
600	600	600	400	400	400	200	200	200	$I_7 = 3.6I_n$
600	600	600	400	400	400	200	200	200	$I_8 = 3.6I_n$
600	600	600	400	400	400	200	200	200	$I_9 = 3.6I_n$

Figure 3. Shading pattern

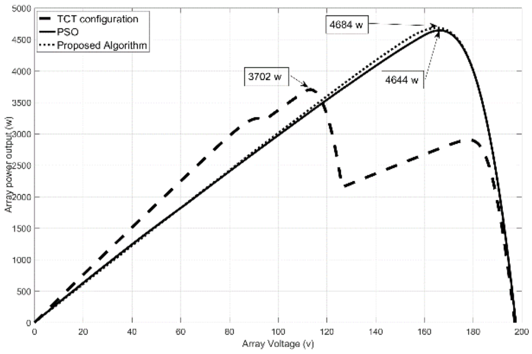
900	900	900	400	400	400	900	900	800	$I_1 = 6.5I_n$
800	600	600	900	900	800	800	900	200	$I_2 = 6.5I_n$
600	900	900	800	400	900	900	200	900	$I_3 = 6.5I_n$
600	900	900	400	900	900	900	200	900	$I_4 = 6.6I_n$
900	600	900	900	800	400	200	900	900	$I_5 = 6.5I_n$
900	600	800	900	900	400	200	900	900	$I_6 = 6.5I_n$
900	800	600	900	400	900	200	900	900	$I_7 = 6.5I_n$
900	900	600	900	900	900	900	200	200	$I_8 = 6.4I_n$
600	900	900	400	900	900	900	800	200	$I_9 = 6.5I_n$

(a)

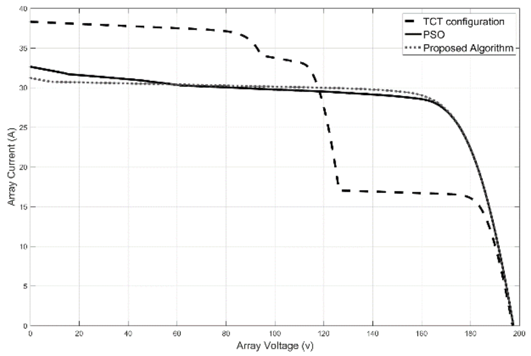
900	600	600	900	900	900	900	800	200	$I_1 = 6.7I_n$
600	900	600	400	900	900	200	900	900	$I_2 = 6.5I_n$
900	800	600	900	900	400	900	200	900	$I_3 = 6.5I_n$
800	900	900	400	400	800	900	900	200	$I_4 = 6.4I_n$
900	600	900	900	800	400	200	900	800	$I_5 = 6.4I_n$
900	900	800	400	400	900	800	900	900	$I_6 = 6.6I_n$
600	900	900	900	900	900	900	200	200	$I_7 = 6.4I_n$
900	600	900	800	400	400	900	900	900	$I_8 = 6.6I_n$
600	900	900	900	900	900	200	200	900	$I_9 = 6.4I_n$

(b)

Figure 4. Reconfiguration results, (a): proposed parallel PSO, (b): PSO [12]



(a)



(b)

Figure 5. Comparison of curves for case 1, (a) I-V curve of the array (b) P-V curve of the array

TCT and literature [12]. Hence, the proposed algorithm is more efficient in comparison with data reported by Babu et al. [12]. The voltage magnitude at the maximum power point of TCT configuration is 113.246 v which is highly less than the nominal voltage of the array. The maximum power output, when the proposed reconfiguration algorithm is used, is about 4684 W, which is 981 W and 40 W greater than TCT configuration and power reported by Babu et al. [12], respectively.

Comparison of the runtime results, best, worst and mean values in two consecutive and parallel implementations with the proposed objective function is presented in Table 4. Due to the stochastic nature of the search process, the simulations are repeated 10 times. The execution speed using parallel computing has increased approximately 2.5 times. This can be a great help especially, in large PV arrays facing semi cloudy weather.

4. 2. shading Pattern Case 2 A long narrow shading pattern is shown in Figure 6. The reconfiguration results of the proposed algorithm and data reported by Babu et al. [12] are shown in Figures 7(a) and 7(b), respectively. The proposed algorithm has less variation in row currents in comparison with literature [12]. This means that the reconfigured array with the proposed algorithm will act

TABLE 3. Theoretical maximum power points for case 1

Array configuration	Row number	Row current	Voltage	Power
TCT	9	3.6	9	32.4
	8	-	-	-
	7	-	-	-
	6	7.2	6	43.2
	5	8.1	5	40.5
	4	-	-	-
	3	-	-	-
	2	-	-	-
	1	-	-	-
	Row number	**Row current**	**Voltage**	**Power**
PSO [12]	9	6.4	9	57.6
	8	-	-	-
	7	-	-	-
	6	-	-	-
	5	6.5	5	32.5
	4	-	-	-
	3	6.6	3	19.8
	2	-	-	-
	1	6.7	1	6.7
	Row number	**Row current**	**Voltage**	**Power**
Proposed algorithm	8	6.4	9	57.6
	9	6.5	8	51.2
	7	-	-	-
	6	-	-	-
	5	-	-	-
	3	-	-	-
	2	-	-	-
	1	-	-	-
	4	6.6	1	6.6

TABLE 4. Runtime results, best, worst and mean values for case 1

	Parallel implementation	Sequential implementation
Execution time (s)	5.163	13.258
Best value	4684	4684
Worst value	4681	4681
Mean value	4682.5	4683.1
Standard deviation	1.5811	1.4491
speedup	2.567	

900	900	900	900	900	900	900	900	900	$I_1 = 8.1I_n$
900	900	900	900	900	900	900	900	900	$I_2 = 8.1I_n$
900	900	900	900	900	900	900	900	900	$I_3 = 8.1I_n$
900	900	900	900	900	900	900	900	900	$I_4 = 8.1I_n$
900	900	900	900	900	900	900	900	900	$I_5 = 8.1I_n$
800	800	800	800	800	800	800	800	800	$I_6 = 7.2I_n$
600	600	600	400	400	400	200	200	200	$I_7 = 3.6I_n$
600	600	600	400	400	400	200	200	200	$I_8 = 3.6I_n$
600	600	600	400	400	400	200	200	200	$I_9 = 3.6I_n$

Figure 6. Shading pattern

900	900	900	900	900	900	800	400	400	$I_1 = 7I_n$
900	900	900	900	900	900	300	700	800	$I_2 = 7.2I_n$
900	900	900	900	900	900	400	800	400	$I_3 = 7I_n$
900	900	900	900	900	900	300	800	700	$I_4 = 7.2I_n$
900	900	900	900	900	900	800	700	300	$I_5 = 7.2I_n$
900	900	900	900	900	900	400	400	800	$I_6 = 7I_n$
900	900	900	900	900	900	800	300	700	$I_7 = 7.2I_n$
900	900	900	900	900	900	800	300	700	$I_8 = 7.2I_n$
900	900	900	900	900	900	800	700	300	$I_9 = 7.1I_n$

(a)

900	900	900	900	900	900	800	700	300	$I_1 = 7.2I_n$
900	900	900	900	900	900	300	400	400	$I_2 = 6.3I_n$
900	900	900	900	900	900	800	800	700	$I_3 = 7.7I_n$
900	900	900	900	900	900	800	700	800	$I_4 = 7.7I_n$
900	900	900	900	900	900	400	300	700	$I_5 = 6.8I_n$
900	900	900	900	900	900	800	800	400	$I_6 = 7.4I_n$
900	900	900	900	900	900	800	400	800	$I_7 = 5.4I_n$
900	900	900	900	900	900	300	700	300	$I_8 = 6.7I_n$
900	900	900	900	900	900	400	300	400	$I_9 = 6.5I_n$

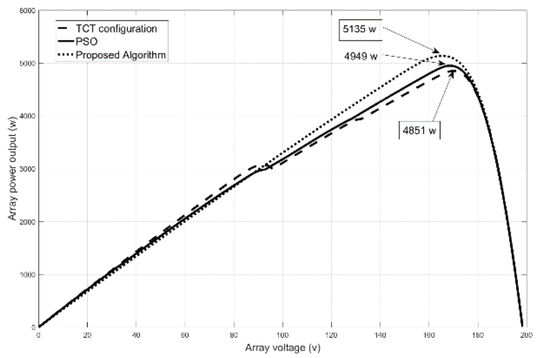
(b)

Figure 7. Reconfiguration results, (a): proposed parallel PSO, (b): PSO [12]

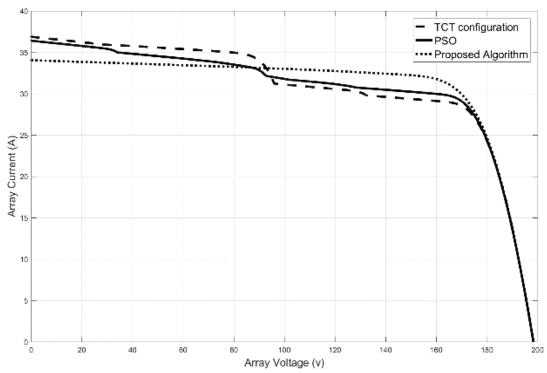
more uniformly in P-V and I-V curves and will be similar to a unity panel receiving equal solar irradiance on its surface. The P-V and I-V curves comparisons are given in Figures 8(a) and 8(b), respectively. The proposed algorithm reaches to a configuration that its output power is 186 W and 284 W higher than PSO reported in literature [12] and TCT configurations, respectively. The theoretical maximum power points for TCT, [12] and the proposed algorithm are represented in Table 5. It is shown in Table 5 that the proposed algorithm has a higher maximum power point than TCT and literature [12]. This means that the reconfigured array is able to produce higher currents and powers for identical voltages than reported data in literature [12] and TCT. This is easily illustrated in Figure 8. The runtime results, best, worst and mean values are given in Table 6. Obviously, parallel computing reduces the simulations runtime and this help to overcome the computational challenges. Also from Table 6, it can be realized that both the sequential and parallel implementations even in the worst case, result in higher values of output powers. This reflects the fact that the optimization algorithm is susceptible to the objective function. In other words, the objective function used by Babu et al. [12] and Deshkar et al. [18] is not suitable to detect the original optimal point.

4. 3. Comparison of other Indicators

In Table 7, the other features of the proposed algorithm and several existing methods are compared. The computation volume of optimization algorithms and objective functions are the complexity comparison index. Although the proposed



(a)



(b)

Figure 8. Comparison of curves, (a) I-V curve of the array (b) P-V curve of the array

TABLE 5. Theoretical maximum power points for case 2

Array configuration	Row number	Row current	Voltage	Power
TCT	4	6.3	9	56.7
	5	-	-	-
	7	6.6	7	46.2
	9	-	-	-
	2	7.6	5	38
	3	-	-	-
	6	7.8	3	15.6
	8	-	-	-
	1	-	-	-
	Row number	**Row current**	**Voltage**	**Power**
PSO [12]	4	6.9	9	62.1
	5	7	8	42
	7	-	-	-
	9	7.2	6	43.2
	2	-	-	-
	3	-	-	-
	6	-	-	-
	8	-	-	-
	1	7.3	1	7.3
	Row number	**Row current**	**Voltage**	**Power**
Proposed algorithm	1	7	9	63
	3	-	-	-
	6	-	-	-
	9	7.1	6	42.6
	2	7.2	5	36
	4	-	-	-
	5	-	-	-
	7	-	-	-
	8	-	-	-

TABLE 6. Runtime results, best, worst and mean values for case 2

	Parallel implementation	Sequential implementation
Execution time (s)	5.945	13.288
Maximum value	5135	5135
Minimum value	5127	5127
Mean value	5133.4	5134.2
Standard deviation	3.3731	2.5298
speedup	2.235	

TABLE 7. Comparison of several metaheuristic-based electrical array reconfiguration methods

Ref.	[18]	[12]	Proposed algorithm
Main objective	Row current minimization	Row current minimization	Irradiation equalization
Solution method	GA	PSO	Parallel PSO
Complexity	high	Moderate	Less
Sensors type	Voltage and current	Voltage and current	irradiance
Array size	9×9	9×9	9×9

algorithm reduces the runtime arising from the simplicity of the calculations and the parallel computing, it can be more expensive due to a large number of irradiation sensors. However, because of increasing the power output, it can effectively overcome additional costs. This increase in power, especially in larger arrays, can justify additional costs.

5. CONCLUSION

Partial shading causes some problems in PV arrays e.g. multiple peak points in P-V and I-V curves and reducing the power output. Reconfiguration of electrical connections between modules is one of the efficient solutions for alleviating the partial shading effects. In this paper, a new non-constrained optimization formulation is proposed. Then, to increase the execution speed, a parallelized PSO is developed to solve the proposed optimization problem. In comparison with TCT configuration, the results show 26.5 and 5.8 percent power improvements in short wide and long narrow shading patterns, respectively. Also, parallel computing leads to an approximately 2.5 folds increase in the computation speed.

6. REFERENCES

1. Tiwari, S.K., Singh, B. and Goel, P.K., "Design and Control of Autonomous Wind–Solar System with Dfig Feeding 3-Phase 4-Wire Loads ", ***IEEE Transactions on Industry Applications***, Vol. 54, (2018), 1119-1127.
2. Sampaio, P.G.V. and González, M.O.A., "Photovoltaic Solar Energy: Conceptual Framework ", ***Renewable and Sustainable Energy Reviews***, Vol. 74, (2017), 590-601.
3. Bayrak, F., Ertürk, G. and Oztop, H.F., "Effects of Partial Shading on Energy and Exergy Efficiencies for Photovoltaic Panels ", ***Journal of Cleaner Production***, Vol. 164, (2017), 58-69.
4. Yang, Z., Duan, Q., Zhong, J., Mao, M. and Xun, Z., "Analysis of Improved Pso and Perturb & Observe Global Mppt Algorithm for Pv Array under Partial Shading Condition ", Control And

Decision Conference (CCDC), 2017 29th Chinese, 549-553, (2017).

5. Belhachat, F. and Larbes, C., "A Review of Global Maximum Power Point Tracking Techniques of Photovoltaic System under Partial Shading Conditions ", ***Renewable and Sustainable Energy Reviews***, Vol. 92, (2018), 513-553.
6. Ram, J.P., Babu, T.S. and Rajasekar, N., "A Comprehensive Review on Solar Pv Maximum Power Point Tracking Techniques ", ***Renewable and Sustainable Energy Reviews***, Vol. 67, (2017), 826-847.
7. Rahimi-Mirazizi, H. and Agha-Shafiyi, M., "Evaluating Technical Requirements to Achieve Maximum Power Point in Photovoltaic Powered Z-Source Inverter ", ***International Journal of Engineering, Transactions C: Aspects***, Vol. 31, No. 6, (2018), 921-931.
8. Vicente, P.S., Vicente, E.M. and Ribeiro, E.R., "A Review of Solar Photovoltaic Array Reconfiguration Methods, Industrial Electronics (ISIE) ", 2015 IEEE 24th International Symposium on, 208-213, (2015).
9. Dhass, A., Natarajan, E. and Lakshmi, P., "An Investigation of Temperature Effects on Solar Photovoltaic Cells and Modules ", ***International Journal of Engineering, Transactions B: Applications***, Vol. 27, (2014), 1713-1722.
10. Pachauri, R., Yadav, A.S., Chauhan, Y.K., Sharma, A. and Kumar, V., "Shade Dispersion-Based Photovoltaic Array Configurations for Performance Enhancement under Partial Shading Conditions ", ***International Transactions on Electrical Energy Systems***, Vol. 28, (2018), e2556.
11. Satpathy, P.R., Jena, S., Jena, B. and Sharma, R., "Comparative Study of Interconnection Schemes of Modules in Solar Pv Array Network ", Circuit, Power and Computing Technologies (ICCPCT), 2017 International Conference on, 1-6, (2017).
12. Babu, T.S., Ram, J.P., Dragičević, T., Miyatake, M., Blaabjerg, F. and Rajasekar, N., "Particle Swarm Optimization Based Solar Pv Array Reconfiguration of the Maximum Power Extraction under Partial Shading Conditions ", ***IEEE Transactions on Sustainable Energy***, Vol. 9, (2018), 74-85.
13. Rani, B.I., Ilango, G.S. and Nagamani, C., "Enhanced Power Generation from Pv Array under Partial Shading Conditions by Shade Dispersion Using Su Do Ku Configuration ", ***IEEE Transactions on Sustainable Energy***, Vol. 4, (2013), 594-601.
14. Dhanalakshmi, B. and Rajasekar, N., "A Novel Competence Square Based Pv Array Reconfiguration Technique for Solar Pv Maximum Power Extraction ", ***Energy Conversion and Management***, Vol. 174, (2018), 897-912.
15. Rao, P.S., Ilango, G.S. and Nagamani, C., "Maximum Power from Pv Arrays Using a Fixed Configuration under Different Shading Conditions ", ***IEEE Journal of Photovoltaics***, Vol. 4, (2014), 679-686.
16. Parlak, K.Ş., "Pv Array Reconfiguration Method under Partial Shading Conditions ", ***International Journal of Electrical Power & Energy Systems***, Vol. 63, (2014), 713-721.
17. Jazayeri, M., Jazayeri, K. and Uysal, S., "Adaptive Photovoltaic Array Reconfiguration Based on Real Cloud Patterns to Mitigate Effects of Non-Uniform Spatial Irradiance Profiles ", ***Solar Energy***, Vol. 155, (2017), 506-516.
18. Deshkar, S.N., Dhale, S.B., Mukherjee, J.S., Babu, T.S. and Rajasekar, N., "Solar Pv Array Reconfiguration under Partial Shading Conditions for Maximum Power Extraction Using Genetic Algorithm ", ***Renewable and Sustainable Energy Reviews***, Vol. 43, (2015), 102-110.
19. Gong, Y.-J., Chen, W.-N., Zhan, Z.-H., Zhang, J., Li, Y., Zhang, Q. and Li, J.-J., "Distributed Evolutionary Algorithms and Their Models: A Survey of the State-of-the-Art ", ***Applied Soft Computing***, Vol. 34, (2015), 286-300.
20. Jordehi, A.R., "Parameter Estimation of Solar Photovoltaic (Pv) Cells: A Review ", ***Renewable and Sustainable Energy Reviews***, Vol. 61, (2016), 354-371.
21. Eberhart, R. and Kennedy, J., "A New Optimizer Using Particle Swarm Theory ", Micro Machine and Human Science, 1995. MHS'95., Proceedings of the Sixth International Symposium on, 39-43, (1995).
22. Imran, M., Hashim, R. and Khalid, N.E.A., "An Overview of Particle Swarm Optimization Variants ", ***Procedia Engineering***, Vol. 53, (2013), 491-496.

Optimal Reconfiguration of Solar Photovoltaic Arrays Using a Fast Parallelized Particle Swarm Optimization in Confront of Partial Shading

H. Heidari[a], M. Tarafdar Hagh[a,b]

[a] *Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran*
[b] *Engineering Faculty, Near East University, North Cyprus, Mersin 10, Turkey*

PAPER INFO

Paper history:
Received 29 May 2019
Received in revised form 1 july 2019
Accepted 05 July 2019

Keywords:
Solar Energy
Electrical Array Reconfiguration
Partial Shading
Photovltaic Arrays

چکیده

سایه جزئی باعث کاهش توان خروجی ماژول های خورشیدی، ایجاد چند نقطه پیک در منحنی های توان-ولتاژ و جریان-ولتاژ و کاهش عمر مفید اینورتر ها و سلول های خورشیدی می شود. بازآرایی آرایش الکتریکی آرایه های فتوولتاییکی که بر اساس تغییر اتصالات الکتریکی توسط دستگاه های کلید زنی است، می تواند به عنوان راه حلی عملی برای جلوگیری از این مشکلات استفاده شود. مطالعات ارزشمندی برای اثبات کارایی آن صورت گرفته است. با این حال، مشکلاتی از جمله پیچیدگی الگوریتم ها، زمان پردازش محاسبات و ناتوانی توابع هدف پیشنهادی در تشخیص بهترین آرایش در آن ها وجود دارد. در این مقاله، مساله بازآرایی آرایش فتوولتاییک ها توسط یک نسخه موازی سازی شده از الگوریتم توده ذرات که به دنبال جستجو برای کاهش اختلاف جریان سطرها می باشد، حل شده است. الگوریتم پیشنهادی در MATAB/Simulink اجرا و به صورت عددی با برخی کارهای مشابه مقایسه شده است. نتایج نشان از سادگی و خروجی های توان بیشتر با وجود کاهش زمان محاسبات دارد. بسته به الگوی سایه جزیی، میزان افزایش توان متفاوت است. بیشترین میزان افزایش توان، ۲٦،٥ درصد توان خروجی آرایه می باشد.

doi*: 10.5829/ije.2019.32.08b.14*