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Reconfiguration and Analysis of PV Array based on Particle Swarm Optimization of Solar Plant

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Abstract – **The major shortcoming in the extraction of electrical energy occurs due to partial shading over a limited area of vast spread solar panels underpinning reduction of efficiency. A number of panels are interconnected in series and parallel to form a photovoltaic (PV) array for large power plants and a shadow over a single cell deteriorates overall performance. As a consequence, several peaks are added to the P-V curve causing hotspots in PV panels, degradation of the PV system, and collapse of tracking algorithms. In order to minimize such issues in PV panels, an effective optimization technique is developed by reconfiguring the panels which are capable of reaching the full global power point in a PV system under partial shading conditions. The study proposes particle swarm optimization (PSO) using PV characteristics of Quaid-e-Azam Solar Plant (QASP) in Punjab, Pakistan. In PSO, electrical connections of PV modules are changed keeping their physical locations unaltered aiming to improve the performance of the PV system. After reconfiguration, the algorithm finds the best combination of PV modules by equalizing the row currents followed by the comparison of row current, voltages, and power of panels. The proposed PSO is proved to be an efficient method for reconfiguring PV modules in very less computational time by increasing the output power of shaded modules.**

Keywords – **Computational efficiency, maximum power point trackers, particle swarm optimization, photoelectricity, photovoltaic systems, power system transients.**

I. Introduction

The enormous amount of energy from the sun that reaches the earth led different researchers to think about photovoltaic techniques to resolve the main issue of the energy crisis. Photovoltaic (PV) cells are used for the conversion of solar energy into electrical energy. The increasing requirements and needs for renewable energy are growing with time due to the shortage of fossil gasoline and the increasing greenhouse effect. Solar energy and wind energy are some of the main and never-ending sources of renewable energy. Compared to other forms of renewable energy, solar PV energy is assumed to be the most affluent due to its potential and availability in every part of the world. Concentrated solar PV (CSPV) is also a paramount form of energy due to its high efficiency of ~71 %; however, its feasibility is validated only in climatically hot regions. Therefore, a bigger-sized PV plant would be a compatible choice as a substitute for CSPV in the countries close to the poles of the earth. In some under-developed and developing countries, there are a lot of energy crises. In order to overcome these issues, researchers and scientists are moving towards the broad spectrum of renewable energy. In recent years, the most important power generation is green electricity from solar energy due to several advantages. Among them, there are zero carbon footprints, zero noise, and less maintenance [1]. For many years, Pakistan has been facing an energy crisis; therefore, we are in dire need of a system that can minimize the difference between demand and supply of electrical energy [2]. In order to interface the PV module with grids, we need to calculate the false circumstances of the running system and machine stabilities. Enhancing the capacity and maximizing the power of PV plants using MPPT and optimizing algorithms become a global strategic goal owing to their smaller efficiency. Various algorithms and methods are discussed in the study to accomplish the maximum power point tracking (MPPT) approach. Many online, offline and hybrid techniques for MPPT are briefly described [3]. According to the survey [4], from 2018 to 2025, related PV capabilities will increase with an annual ratio of about 55 % of its total capacity. There are many configuration methodologies present in the literature which help regulate the shape of the PV array [5]. Punjab is blessed with a good supply of solar energy and uses it for power generation. The output of the PV system is directly affected by radiation from the sun and climate change. The generation of power from solar PV cells needs a well-arranged and properly designed mechanism. If a larger-scale PV model is linked with a grid station, there will be a profound and intense effect on the grid. In order to solve mathematical problems and other scientific hurdles, many computations are available and discussed in the next section.

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II. Algorithms for Optimization and Reconfiguration

For large photovoltaic energy technology plants, there is a variety of panels that are further connected in series and parallel combination manner for the shaping of PV array. In this way, the partial shading condition (PSC) will result in a decrease in electricity output. The modules within the array will deliver different row currents and disorders in the MPPT algorithm [6]. Therefore, in order to maximize the power extraction from the PV array, the panels need to be reconfigured. In [7], solar PV power systems suitable for stand-alone operation are designed to support small rural and urban housing and business communities. In research [8], many methods and algorithms are presented for the proper configuration of the PV array. Semitransparent photovoltaic (STPV) cells are integrated into sunscreen structures in [9] to reduce lighting requirements. The results of using STPV show annual net energy savings of up to 7 % and electricity savings of up to 60 % during the day. Total cross-tied (TCT) configuration is a well-known technique used for PV arrays. It is the mostly used topology available for the purpose of the alignment, positioning, and configuration of the PV arrays. With the help of this technique, the problem created by the irradiance and temperature can be solved to stabilize voltage, current, and power. It has an advantage over other linking methods as in this method, the losses are reduced to a minimum, and it gives the best result under different shading patterns [10], [11]. The performance analysis of TCT is tested on different shading patterns, and results are verified after simulations [13]. Dominance square-based array reconfiguration scheme is evaluated [12] for power loss reduction in solar PV systems. Based on that research, row currents difference has been improved, V-I and P-V curves are obtained with more accuracy.

Bridge linked technique has also been used for the reconfiguration of the PV modules. In this methodology, the cells are arranged in a pattern of a bridge rectifier [14]. A lot of research is present on the comparison of all reconfiguration techniques. Based on research [15], TCT has shown good results and greater efficiency, series-parallel has the least efficiency, bridge-link and honey-comb show results less efficient than TCT in case of different shading conditions. In some research, the cost has been compromised and Sudoku has been given importance because of fewer power losses and an accurate V-I curve. There are many disadvantages to physical relocation-based methods such as laborious work, complex rewiring, and a large number of interconnection ties. In order to resolve all these issues, the best way is to use an optimization algorithm that must be capable of handling multi-model objectives and finding out the best-optimized solution. A genetic algorithm (GA) has been in use for solar systems for reconfiguration under partial shading conditions. With the help of the GA, a great amount of power from the PV array has been generated [17] but this method also has drawbacks, including bad convergence, large computational steps, and requiring wide search space. In [16] the impact of stochastic PV generation on the dynamic stability of grid-connected PV systems is described using a probabilistic small-signal analysis approach.

III. Methodology

A. Proposed Particle Swarm Optimization Algorithm

Particle swarm optimization (PSO) is basically a population-based algorithm. It was first presented by Kennedy and Eberhart in 1995 and later on, it was further modified by many researchers to bring modifications according to the need and advanced parameters [6]. It is applied to almost every technical educational field for the purpose of computation and system design. PSO works on a group of solutions rather than working on a single solution and then finally the best optimal is chosen as the final result. It consists of a large number of iterations and finally decides on the best objective or fitness function. PSO can easily work on nonlinear problems and the algorithm works in the same way without being disturbed by the nonlinear data entry at any point of the computational stage [18].

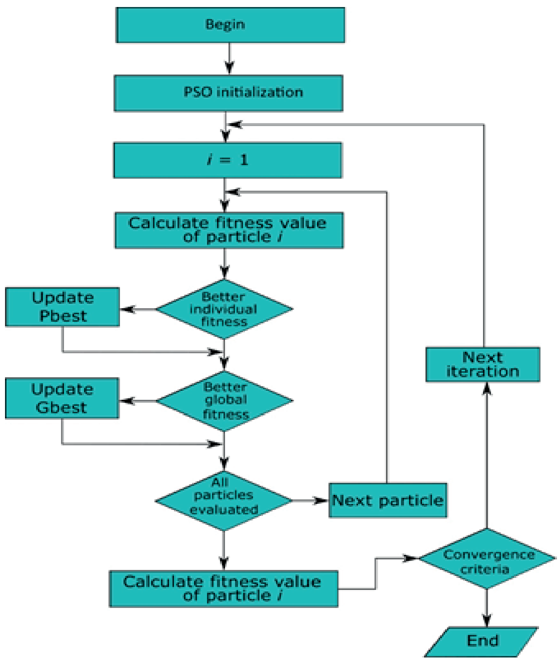

Fig. 1. PSO algorithm.

There are many variables, fitness values, and other parameters to be designed in such a way as to achieve the best optimal solution. From studies and research, it has been inferred that the PSO has a high convergence rate as compared to the GA [19]. When an advanced PSO algorithm is combined with other algorithms, especially with the GA, its convergence rate becomes higher and works more efficiently for finding the optimal result [20]. The purpose of the proposed PSO method is to make a base for the solar PV array reconfiguration under partial shading conditions (PSC). This algorithm follows the path of the best and most feasible solution by updating the position of the particle at every step. The working of the algorithm is described in Fig. 1.

B. Updating the Velocity and Position of Each Particle

Initially, all the parameters are randomly selected and then values of position and velocity are updated by the following equations:

$$V_i(t+1) = wV_i(t) + c_1r_1(P_{\text{best}} - X_i(t)) + c_2r_2(G_{\text{best}} - X_i(t)); \quad (1)$$

$$X_i(t+1) = X_i(t) + V_i(t+1). \quad (2)$$

Here, i is the particle index, population size is 50, $w = 0.9$ is the inertia coefficient, c_1 and c_2 are acceleration coefficients computed in (3), r_1 and r_2 are random values in the range [0 1], $V_i(t)$ is the velocity of the particle at time t, $X_i(t)$ is the position of the particle at time t, P_{best} is the particles individual best solution at time t, and G_{best} is the global best solution at time t.

$$c_2 = \frac{\frac{V_{\text{mp}}}{V_{\text{oc}}}-1}{\text{Log}(1-\frac{I_{\text{mp}}}{I_{\text{sc}}})},\ c_1 = \left(1-\frac{I_{\text{mp}}}{I_{\text{sc}}}\right)e^{\frac{-V_{\text{mp}}}{(c_2)(V_{\text{oc}})}}, \quad (3)$$

where V_{oc}, I_{sc}, and I_{mp} are open-circuit voltage, short circuit current, and maximum point current respectively for a PV unit.

C. Upgradation of G_{best} and P_{best} by Calculating Fitness Function (F) of Each Particle

First of all, this algorithm is used to pick out a random number of particles N from a D dimensional search space. In this space, each and every particle represents one of the solutions which have a definite position and velocity. According to the movements of these particles, there are two positions. One of them is the individual best position P_{best} and the other one is the global best value G_{best}. P_{best} is obtained through all preceding iterations by i^{th} particle and G_{best} is obtained with the sum of all particles within all past iterations. The optimal objective function is adopted according to their recorded P_{best} and G_{best} values. PSO evaluates a solution during each iteration which is then analyzed by the required fitness function F. Here, each result is termed as a particle then these particles move around to choose the best feasible solution to optimized solution. A small population results in fast convergence to local maxima or extrema which quickly locates the personal best targets of individual particles. However, in a certain scenario, if the location of the best particle is not the one that is globally the most optimum one, all particles will be floating in the misguided neighbourhood even for a large number of iterations. This will further reduce the performance of the system due to higher computational costs. One solution to this problem is increasing the number of swarms, which increases the probability of finding the target location in a short span of time. The Fitness Criteria for individual best can be found in (4)–(6).

If $F(t+1) > F_{P\text{best}}(t)$ then

$$P_{\text{best}}(t+1) = P_{\text{best}}(t); \quad (4)$$

If $F(t+1) \leq P_{\text{best}}(t)$ then

$$P_{\text{best}}(t+1) = X_i(t+1); \quad (5)$$

$$F_{P\text{best}}(t+1) = F(t+1). \quad (6)$$

The Fitness Criteria for global best can be found in (7) and (8).

If $F(t+1) \leq F_{G\text{best}}(t)$ then

$$G_{\text{best}}(t+1) = P_{\text{best}}(t+1); \quad (7)$$

$$F_{G\text{best}}(t+1) = F_{P\text{best}}(t+1). \quad (8)$$

Here $F(t+1)$ is the fitness function value at time t+1, $F_{P\text{best}}(t)$ and $F_{P\text{best}}(t+1)$ arethe fitness values of the individual best position at time t and t+1, respectively, $F_{G\text{best}}$ (t) and $F_{G\text{best}}(t+1)$ are fitness values of the global best position at time t and t+1, respectively, $P_{\text{best}}(t+1)$ and $P_{\text{best}}(t)$ are individual best positions at time t+1 and t, respectively, and $X_i(t+1)$ is the position of the ith particle at time t.

IV. Statement of the Problem

In this paper, the PV array reconfiguration under partial shading is presented by maintaining the same PV output and finding the best-optimized combination by analyzing fitness function constraints with the objective of equalizing PV row currents for better performance based on the particle swarm optimization algorithm.

A. Objective Function

The objective function of equalizing PV row currents is defined as (9)–(12).

$$A = \begin{bmatrix} X_{1,1} & X_{1,2} & \cdots & X_{1,j} \\ X_{2,1} & X_{2,2} & \cdots & X_{2,j} \\ \vdots & \vdots & & \\ X_{i,1} & X_{i,2} & \cdots & X_{i,j} \end{bmatrix}; \quad (9)$$

$$I_{r1} = \sum_{m=1}^{j} X_{1,m}; \quad (10)$$

$$I_{r2} = \sum_{m=1}^{j} X_{2,m}; \quad (11)$$

$$I_{r3} = \sum_{m=1}^{j} X_{i,m}. \quad (12)$$

A is a matrix of PVs in which each entity such as $X_{1,1}$ is considered a PV unit and connected in series and parallel combination with $X_{1,2}$ to $X_{2,1}$ and $X_{2,2}$ as shown in the proposed configuration diagram (Fig. 3). Each unit has a flowing current depending on its PV rating, surrounding temperature, and irradiance levels. I_{r1}, I_{r2} and I_{ri} are the summations of PV 1st, 2nd, and i^{th} row current values, respectively, and the goal is to achieve (12) which states that all PV rows should have the same current values.

$$I_{r1} = I_{r2} = I_{ri}. \quad (13)$$

B. Constraints

After finding an optimized solution by reconfiguration the power calculation is made based on the following equations.

$$a = \acute{I}_{\text{sc}}\frac{I_{\text{sc}}}{100},\ b = U_{oc}\frac{V_{\text{oc}}}{100}; \quad (14)$$

$$D_1 = a\frac{Ir}{Ir_{\text{ref}}}(T - T_{\text{ref}}) + (\frac{Ir}{Ir_{\text{ref}}} - 1); \quad (15)$$

$$V_{\max 1} = c_2 V_{oc} \log \frac{\left(1-\frac{(0-D_1)}{I_{sc}}\right)}{c_1+1} - b(T-T_{ref}) - R_s D_1; \quad (16)$$

$$V_{r\max 1} = 0 + b(T-T_{ref}) - R_s D_1; \quad (17)$$

$$I_{\max 1} = I_{sc}\left(1 - c_1\left(e^{\frac{V_{r\max}}{(c_2)(V_{oc})}} - 1\right)\right) + D_1; \quad (18)$$

$$P_{\max 1} = V_{\max 1} \times I_{\max 1} \times 0.9\,. \quad (19)$$

$V_{\max 1}$, $I_{\max 1}$, and $P_{\max 1}$ are updated values after each iteration. $\acute{U}_{oc}$, and $\acute{I}_{sc}$ are open-circuit voltage coefficients, and short circuit current coefficients, respectively, for a PV unit. The algorithm should work until it satisfies the equation

$$P_{\max 1} \geq P_{mp}. \quad (20)$$

C. Fitness Function

Each solution after reconfiguration assesses its fitness function based on the (21):

$$\text{Fitness} \lim_{i \to n} \frac{F(X_i) \;\rightarrow\; \text{Sum of each row current is}}{\text{equal to sum of other row currents}}, \quad (21)$$

where n is the total number of iterations for each particle and the value of current is after each iteration.

D. Yearly Energy Intensity Report for Quaid-e-Azam Solar Plant (QASP)

Punjab Province is located within the mid-latitude zone, where the solar radiation intensity is high, illumination time is long, and the total annual radiation quantity is 6100 MJ/m^2 to 7200 MJ/m^2 as shown in Table I. From Table I, the sunshine hours in Bahawalpur lie between 2900 h to 3300 h and the annual average sunshine hours are 3201 h. With strong sunlight, lack of overcast, long sunshine duration averaging 3101 h yearly, and high radiation intensity averaging 6408 MJ/m^2 yearly in Bahawalpur District, the solar resources are very rich. The location of the power plant is a desert area with extreme weather conditions with an ambient temperature rising up to 50 °C.

E. Solar Module Details

The solar panel manufacturer in QASP is "JA SOLAR" and each module has an efficiency of 15.59 %. The rated maximum power at standard test conditions (STC) is 255–260 W and each module has a total of 60 cells. All details of the solar panel module are given in Table II.

F. Characteristics of a PV Module

The design of PV in QASP is based on 25 °C and 1000 W/m^2. Each PV can give 37.8 V in open circuit conditions and the maximum power point voltage that can be achieved is 30.3 V. The PV characteristic of QASP is briefly mentioned in Table III.

G. PV Configuration of QASP and the Proposed PV Configuration

In 1 MW plant, there are a total of 13 combine boxes. Each box has 18 strings and 20 modules as shown in Fig. 2.

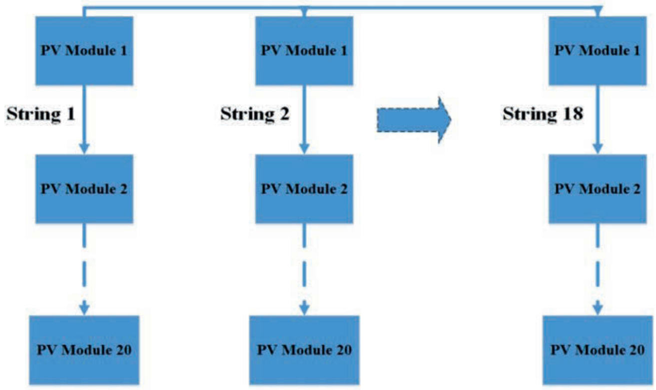

Fig. 2. The layout of one combine box of QASP.

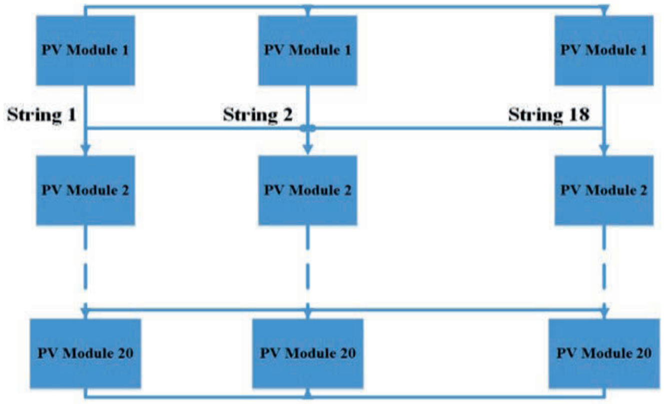

Fig. 3. The proposed configuration.

In the proposed configuration, each PV module must be connected to all other modules in a series-parallel combination as shown in Fig. 3. The main advantage of this combination is that during the reconfiguration algorithm any module can be reconfigured or replaced with any other module in the whole PV configuration in order to find the bestoptimized combination.

TABLE I
MONTHLY DATA FOR ENERGY INTENSITY

Month	Standard radiation (MJ/m^2)	Sunshine hours
Jan	354	223
Feb	411	224
Mar	536	271
Jul	651	276
Aug	637	282
Sep	606	285
Oct	496	293
Nov	386	263
Dec	343	226

TABLE II

SPECIFICATIONS FOR SOLAR MODULE

Manufacturer	JA Solar
Type	Polycrystalline
Rated maximum power at STC	255 W + 5 W
Module efficiency	15.59 %
Number of cells	1×60
Total capacity of plant (MW)	100.00
Quantity of modules	392 165.00
Technology	Si-Poly
Model	JAP6(BK) 60/255/3BB
Class of module	A
Module size (W×L)	0.991×1.650 m^2
Rough module area	1.64 m^2
Quantity of arrays	9804.00
Numberof modules in a string	20.00

TABLE III

PV CHARACTERISTICS/SPECIFICATIONS OF THE MODEL

Reference temperature	25 °C
Open circuit voltage (V_{oc})	37.8 V
Maximum power point voltage	30.3 V
Maximum power P_{max}	255.0 W
Shunt resistance	250 Ω
Diode saturation current	0.301 nA
Direct voltage of bypass diodes	−0.7 V
Specified Pmax-temp. coeff	−0.41 %/°C
Reference temperature	25°C
Open circuit voltage (V_{oc})	37.8 V
Reference irradiance	1000 W/m^2
Short circuit current (I_{sc})	8.98 A
Maximum power point current	8.42 A
Isc-temperature coefficient	5.4 mA/°C
Series resistance	0.34 Ω
Voc-temperature coefficient	−127 mV/°C
Diode factor-temp.coeff.	0.0001/°C
Diode quality factor gamma	1.02
Reverse characteristics (dark)	3.20 mA/V^2
No. of bypass diodes per module	3

V. MATLAB BASED RESULTS

A. Working of the Proposed Algorithm

PV calculation is based on PV characteristics of QASP data as mentioned in previous tables. The working of the proposed algorithm is described below. When a user runs this model, it asks about input parameters in three steps as mentioned in Table IV.

TABLE IV

ALGORITHM INPUTS

STEP 1
ENTER INPUT DATA
Enter maximum iteration
Enter no. of particles
STEP 2
ENTER PANEL DETAILS
Number of panel rows
Number of panel columns
The amount of minimum irradiance (W/m^2)
The amount of maximum irradiance (W/m^2)
Temperature (°C)
STEP 3
HOW WOULD YOU LIKE TO TAKE IRRADIANCE?
(i) Random value for all panels
(ii) Fixed value for each row
(iii) Enter manually for every panel

Here, the user has three choices in order to spread irradiance levels on modules. If a user selects a random value for all panels, then the algorithm sets random values on all PV modules by itself. In the option “fixed value for each row”, the algorithm spreads the same value of irradiance on all modules of the same row. The last option is to enter manually for every panel, where the user can write manually each value on the module. After entering these input details, the algorithm makes a matrix based on given data and performs an analysis that provides initial information about module configuration, irradiance level, module current, row currents, and module power. After getting all details of the initial parameters, the proposed algorithm reconfigures the complete matrix and performs iterations in order to achieve an optimized combination. The best combination from reconfiguration is the one that includes the minimum row current difference. After finding that solution, the algorithm again performs analysis and gives final information about module configuration, irradiance level, module current, row currents, and module power. In the end, it makes the comparison between initial values and the ones after reconfiguration in the command window of MATLAB and also in graphical form.

VI. RESULTS AND DISCUSSION

These results are achieved using input parameters as mentioned in Table V.

TABLE V

PARAMETERS FOR SIMULATION

Number of iterations	100
Number of particles	50
Number of rows	4
Number of columns	4
Minimum irradiance	100 W/m^2
Maximum irradiance	800 W/m^2
Temperature	25 °C
Spread irradiance on panels	Fixed value for each row

A. Comparison of Irradiance Level (W/m^2) and Panel Configuration

Based on Table V, the algorithm makes a 4×4 matrix and spreads irradiance on each panel between its minimum value and maximum value. As the selected method here is a fixed value for each row and the range of irradiance is 100–800 W/m^2, it will spread irradiance randomly on the complete matrix but the value of irradiance on each row will be the same as shown in Fig. 4.

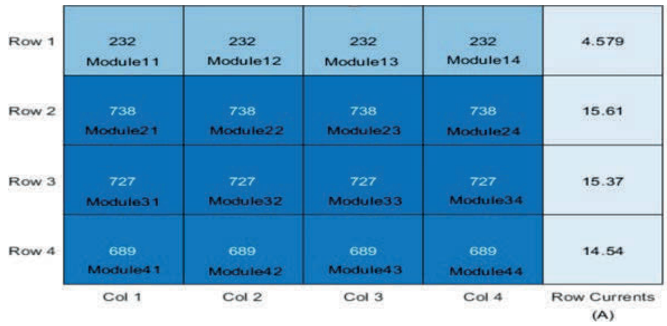

Fig. 4. Initial configuration of panels.

The first row has very low irradiance as compared to other rows and each module of its row has an equal irradiance level. The first row of the matrix is shaded and has very low irradiance as compared to other rows. After reconfiguration, all modules which have minimum irradiance are reconfigured as shown in Fig. 5.

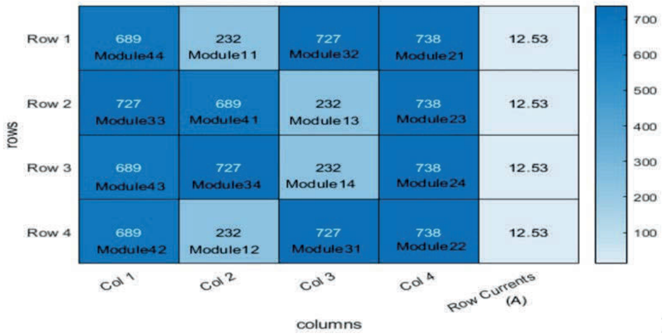

Fig. 5. Final configuration of panels.

B. Comparison of Row Currents (A)

Based on the initial irradiance level on panels, the value of current in each module of the first row is low compared to other row modules because the first row has a low irradiance level as shown in Fig. 6 where the total current in the first row is not equal to other rows.

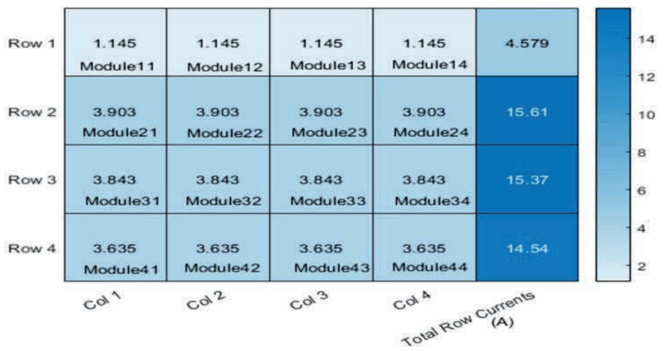

Fig. 6. Initial currents (A) of panels.

It has very little current which causes multi peaks in the PV curve and hotspots in PV panels. After reconfiguration, the issue is solved as shown in Fig. 7.

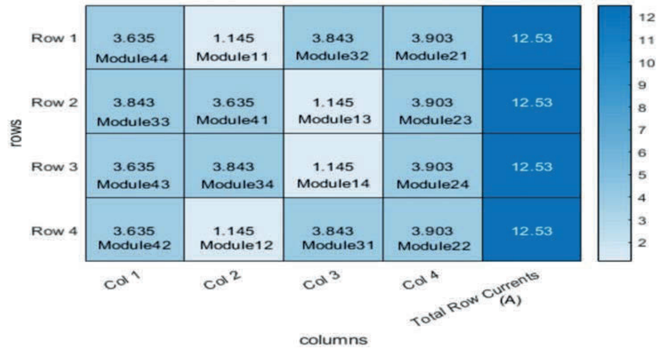

Fig. 7. Final currents (A) of panels.

Here PV is reconfigured in such a way that each row has an equal amount of current. In the first row, the total current is equalized with respect to other rows. A comparison between initial and final row currents of 4×4 matrices is shown in Fig. 8. After reconfiguration, the current in the first row is equalized with respect to other rows and that is the main objective of this algorithm to minimize the difference between row currents by finding the best combination of PV modules.

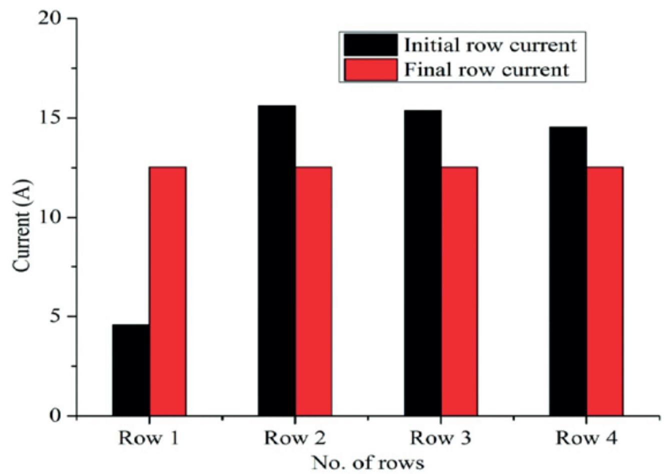

Fig. 8. Comparison of row currents before and after configuration.

C. Comparison of Power (W)

Based on the initial irradiance level on panels, the value of power in each module of the first row is low compared to other row modules because the first row has a low irradiance level as shown in Fig. 9.

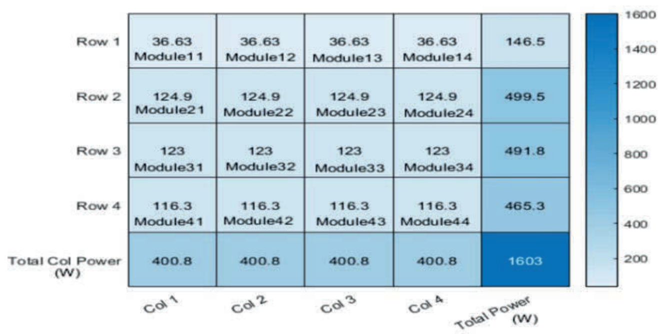

Fig. 9. Initial power of panels.

In Fig. 9, the power in the first row is not equal to other rows. After reconfiguration, the power of the first row is also equalized with respect to other rows as shown in Fig. 10.

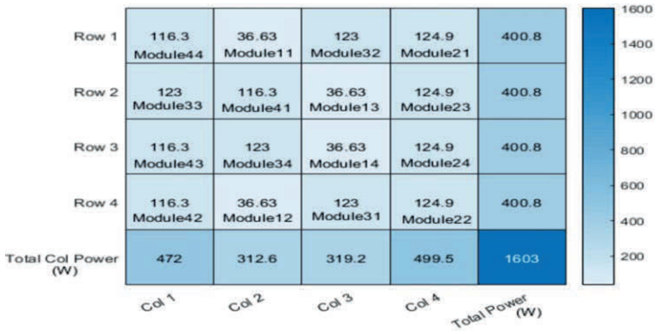

Fig. 10. Final power of panels.

A comparison between the initial and final row power of 4×4 matrices can be seen in Fig. 11.

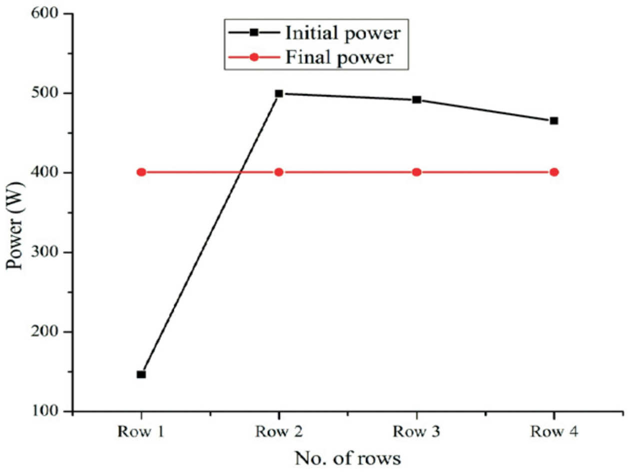

Fig. 11. Comparison of power before and after configuration.

After reconfiguration, the power in the first row is equalized with respect to the other rows. The other advantage of the proposed algorithm is that it has not affected total output power. It can be seen that, even after reconfiguration, the total power of the system is the same as before reconfiguration. The goal of this algorithm is to find the best combination of PV modules by equalizing the row currents so that all issues which come due to large differences between row currents can be minimized such as hotspots in PV panels, glass cracking, and disorder in PV curve because these issues will reduce the life span of the PV system.

D. PSO Convergence and Computational Time

PSO convergence refers to a local optimum point where all personal P_{best} or alternatively the swarm's best-known position G_{best} approach a local optimum of the problem regardless of how the swarm behaves. As PSO initiates from random particles up to the best and optimized combination of particles after all iterations, the computational time is the total time taken by this PSO algorithm from the initial stage to its final stage. PSO convergence based on Table V is shown in Fig. 12.

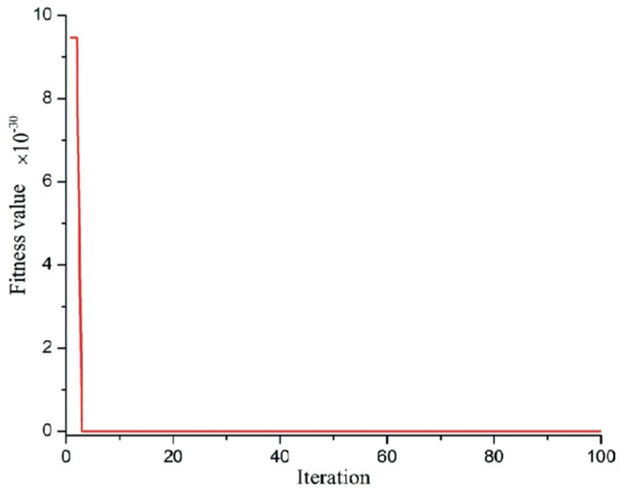

Fig. 12. PSO convergence.

From this graph, it can be seen that after almost less than 20 iterations this algorithm is converged and computation for the total number of 100 iterations and 50 particles is achieved in 4.0894 s. The total time taken by this algorithm mainly depends on the number of iterations and the number of particles. To obtain more and best optimized combinations, it is good to increase the number of iterations and particles because the algorithm will get more search space, and chances of finding the best combination will increase but there is also one thing that must be noted that due to an increasing number of iterations and particles, the algorithm will take more time in order to achieve convergence. Therefore, all these parameters must be selected after the proper calculation of any PV system design.

VII. Conclusion

Photovoltaic systems are of great interest among renewable sources as the energy demand has increased exponentially. The optimization task of different row current minimization for PV array for power maximization is proposed and solved using the PSO method. According to the results of the analysis, the proposed method is capable of achieving a fairly uniform distribution of shade across the panel. As a result, shadow concentration on a specific area is avoided, resulting in higher power output. Furthermore, the difference in row current is greatly reduced, resulting in a better I-V characteristic of the PV array.

The proposed research will enable engineers to monitor and analyse PV systems on a real-time basis, as the project has effective scope in the solar industry. The power quality of the system will be improved, which will result in low loss. As smart grids are the future of power systems, these grids demand side management as well as power flow from renewable energy sources to provide low power cost, minimize system losses and increase power quality. High computing gadgets and computers require refined power supply without harmonics due to high operational frequency. Moreover, PSO has the ability to search for the optimal solution more quickly and converge in a few iterations with few settings of the parameters and simple implementation.

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