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Optimal Solar Array Configuration for Multiple Shade Patterns

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***Abstract*—The Renewable Energy Sources (RES) participating in the stable and reliable grid operation is increasing exponentially. Solar PV has a major contribution to the increased grid integration of RES. Optimal output should be obtained from the connected solar PV arrays. These arrays are connected in series and parallel to operate at Maximum Power Point (MPP) under normal conditions. However, under partially shaded conditions, some panels may be shaded, and the output of the whole array may not be optimized. Switching of panels is utilized to obtain maximum output in such conditions. In this paper, multiple metaheuristic methods like Particle Swarm Optimization, Manta Ray Foraging Optimization, Gorilla Troop Optimizer, and Bald Eagle Search are employed to obtain the optimal solar array configuration in multiple shaded patterns for a 9 $\times$ 9 array. These configurations are obtained under individual shading patterns, and multiple shaded patterns are considered simultaneously. MATLAB is used for implementing the metaheuristic techniques.**

***Index Terms*—MPPT, partially shaded, PSO, MRFO, GTO, BES, solar arrays**

I. Introduction

Renewable Energy Sources (RES) have increased their contribution to power generation. This increase is due to environmental concerns and policies introduced by various governments worldwide. Solar PV is the largest contributor to RES generation [1]. Among the various RES, solar PV is more sustainable, abundant, highly reliable, and non-detrimental. Partial Shading Condition (PSC) is responsible for substantially reducing solar PV output power, thus leading to suboptimal performance. PSC occurs due to non-uniform irradiation across solar PV panels. Non-uniform irradiations are observed over solar PV for various reasons like shadows (clouds, trees, and buildings), dust particles, bird droppings, manufacturing defects, etc.

PSC leads to modules receiving non-uniform radiation, which causes a mismatch in the current generation within the strings of the array. The mismatch in the current generation may further lead to hot spot formation and damage to the solar array [2]. A permanent decrease in performance and output will be observed.

One of the methods to reduce the effect of PSC is the use of bypass diodes. It helps in improving the power output of the system. The demerit of this system is that it introduces multiple peaks in the P-V characteristics of the array. Different MPPT algorithms are in place for tracking global peaks in P-V characteristics, but the implementation requires high-rated converters, which are costly [3].

The effects of PSC can also be diminished by the use of solar PV reconfiguration. In this method, the positions of the solar PV array modules are rearranged with the help of switches. The rearrangement is performed with the objective of achieving uniform radiation across all strings of solar PV array modules. Some of the established interconnection schemes are series, parallel, series-parallel, total cross-tied (TCT), honeycomb, and bridge link [4]. In these methods, TCT is more efficient in terms of fill factor and output power.

The reconfiguration techniques are classified as static and dynamic. These techniques are defined as i. Without the altering of electrical connections, physical relocation is performed. ii. Electrical connections are modified without performing physical relocation. [4]. Some of the methods applied for static reconfiguration are the Zig-zag Technique, Su Do Ku reconfiguration, Futoshiki Puzzle, Competence Square, Skyscraper Technique, and Magic Square. Methods applied for dynamic reconfiguration are Irradiance Equalization (IE), Electrical Array Reconfiguration (EAR), using Artificial Intelligence (AI), and Adaptive Array Reconfiguration (AAR) [5]. Real-time validation of the effects of PSC on the performance of solar PV array is presented in [6] and [7]. In literature, metaheuristic methods have been implemented to solve PSC like [8], [9] and [10].

The solar array setup in this research work is considered to be 9X9 in dimensions. The heuristic methods applied are: Particle Swarm Optimization (PSO) [11], Manta Ray Foraging Optimization (MRFO) [12], Gorilla Troop Optimizer (GTO) [13], and Bald Eagle Search (BES) [14]. These optimization methods have been implemented through MATLAB.

The contributions of this paper can be listed as:

- The elements of the search agents in the metaheuristic methods are updated in each iteration as a matrix and not as individual values.
- Metaheuristic methods are applied to obtain the optimal solar array configuration for different shading patterns.
- Metaheuristic methods are applied to find optimal solar array configuration for all the shading patterns simultaneously and a detailed comparison is presented.
- Modern metaheuristic methods are selected and their performance is compared with classical methods.

II. System Model

The PV array is made up of multiple PV cells, which will convert irradiation to electrical energy. A PV cell is represented by a current source, anti-parallel diode, series resistance, and parallel resistance. The current in this PV cell is represented by Eq 1.

$$I_{cell} = I_{pv} - I_{sh} - I_{di} \tag{1}$$

where I_{pv} is the current generated due to irradiation, I_{sh} is the current in shunt resistance, and I_{di} is the current in anti-parallel diode and expressed as Eq 2.

$$I_{di} = I_o\left(\exp\left(\frac{V_{di}}{aV_t} - 1\right)\right) \tag{2}$$

where I_o is diode saturation current, a is its ideality factor, whereas V_t is the thermal voltage given by Eq 3.

$$V_t = \frac{N_s kT}{q} \tag{3}$$

where N_s is the number of cells in series, k is Boltzmann constant, q is the electron charge and T is the temperature in Kelvin.

The current in the shunt resistance is given by Eq 4.

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \tag{4}$$

The current generated due to the incidence of irradiation is presented in Eq 5.

$$I_{ph} = \frac{G}{G_o}\left[I_{sc} + k_i\left(T - T_o\right)\right] \tag{5}$$

where I_{sc} is short circuit current, G_o and G are ideal and actual irradiation respectively, and T_o and T are ideal and actual temperatures, respectively.

TCT configuration is one of the most acceptable configurations to mitigate PSC and enhance the output. The calculation of row currents is given as Eq 6.

$$I_{R_i} = \sum_{j=1}^{r_n}\left(\frac{G_{ij}}{G_o} I_{m_{ij}}\right) \tag{6}$$

where r_n is the number of rows

Voltage at the terminals of the array is given in Eq 7

$$V_{\text{array}} = \sum_{i=1}^{r_n} V_{m_i} \tag{7}$$

where I_m and V_m are the row currents and voltages, respectively.

The objective function relates to the ability of the reconfigured system to produce maximum power. The fitness function for the same is represented through Eq 8.

$$max f = A_p + \frac{W_e}{P_e} + P_a \times W_{P_a} \tag{8}$$

where A_p is the array power, P_e is the error between maximum power acquired through curves and local values for each row, P_a is the array output without implementing bypass diodes, and W_e and W_{P_a} are the weights attached to the respective power. In this study, the weights are considered to be 10 [4].

Array Power is given as Eq 9.

$$A_p = \sum_{i=1}^{r}(I_i \times V_i) \tag{9}$$

where r is the number of rows, V_i and I_i are the respective voltage and current values of i^{th} row. Eq 10, gives the error power.

$$P_e = \sum_{i=1}^{r}\left|P_p - (I_i \times V_i)\right| \tag{10}$$

where P_p is the peak value of output power.

III. Metaheuristic Methods

The different metaheuristic optimization methods applied in this research work are explained briefly in this section. The search agents used in these methods are updated as matrices in each iteration. Thus, all the methods have been modified accordingly.

A. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a swarm-based optimization method. A population of particles is generated, and these particles move in the search space to find the optimal solution. The velocity for each particle is evaluated in every iteration, which decides the direction of its movement.

B. Manta Ray Foraging Optimization

Manta Ray Foraging Optimization (MRFO) is a search method based on the foraging behavior of manta rays. The foraging behavior is divided into three distinct stages. These stages are chain, cyclone, and somersault foraging. In the first stage, a chain is formed and the manta ray follows the manta to which it is connected. In the second stage, the manta tries to follow the preceding manta and also tries to move towards the optimal solution. In the third stage, the manta moves around the optimal solution.

C. Gorilla Troop Optimizer

Gorilla Troop Optimizer (GTO) is a search method based on the gorilla troop behavior. All activities undertaken by a gorilla troop are converted into a mathematical model. Exploitation and exploration are considered in this method by following the optimal solution and migration process, respectively.

D. Bald Eagle Search (BES)

Bald Eagles are known for hunting fishes. BES mimics the foraging and social behavior of bald eagles. The BES method is implemented through three stages. In the first stage, the region with high prey is demarked. In the second stage, the search agent enters the selected area of prey. In the last stage, the bald eagle attacks the prey.

The equations used in the above-mentioned optimization techniques can be referred to in the references indicated earlier in Section I for detailed understanding.

IV. Results

The research work presented in this paper compares the performance of different optimization methods for optimal solar PV array configuration having a size of 9X9. The performance of these methods is compared for individual shaded conditions and a combination of these conditions. The different shaded conditions considered in this research work are presented in Figs 1. The numbers in each block represent the irradiation being incident on a particular part of the solar PV array.

The metaheuristic techniques applied to obtain the optimal solar PV array configuration are: PSO, MRFO, GTO, and BES. These methods were executed 40 times and the aggregated results are presented.

A comparison of the outputs obtained from these methods applied to individual patterns is shown in Table I. The better solutions for each pattern are shown in italics. It can be observed that GTO and BES are able to obtain the optimal solutions for all the patterns, whereas MRFO excels only in patterns 2 and 4. PSO is unable to get the best results for any of the patterns.

Fig 2, 3, 4, and 5 show the optimal patterns obtained through the applied optimization techniques for different patterns. It can be observed that even though the optimal output value is the same for some patterns, the optimal solar PV configuration differs with the optimization techniques.

Pattern1

900	900	900	900	900	900	400	400	400
900	900	900	900	900	900	400	400	400
900	900	900	900	900	900	400	400	400
900	900	900	900	900	900	400	400	400
900	900	900	900	900	900	400	400	400
900	900	900	900	900	900	400	400	400
600	600	500	500	400	400	200	200	200
600	600	500	500	400	400	200	200	200
600	600	500	500	400	400	200	200	200

(a) Pattern 1

Pattern2

900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	900	900
900	900	900	900	900	600	600	400	400
900	900	900	900	900	600	600	400	400
900	900	900	900	900	600	600	600	600
900	900	900	900	900	600	600	600	600

(b) Pattern 2

Pattern3

900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	900	900
600	600	600	900	900	900	900	900	900
600	600	600	400	400	400	200	200	200
600	600	600	400	400	400	200	200	200
600	600	600	400	400	400	200	200	200

(c) Pattern 3

Pattern4

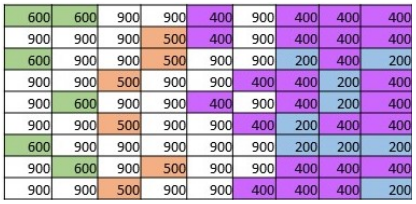
900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	900	900
900	900	900	900	900	900	900	700	700
900	900	900	900	900	900	900	700	700
900	900	900	900	900	900	900	700	700
900	900	900	900	900	900	400	400	400
900	900	900	900	900	900	400	400	400
900	900	900	900	900	900	300	300	300
900	900	900	900	900	900	300	300	300

(d) Pattern 4

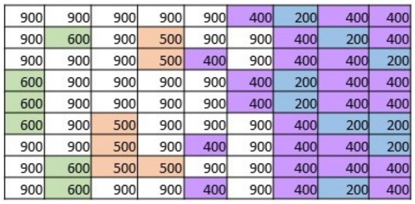
Fig. 1: Shading Patterns

TABLE I: Performance Comparison of Metaheuristic Techniques

Shaded Pattern	**PSO**	**MRFO**	**GTO**	**BES**
Pattern 1	47.7	48.6	*49.5*	*49.5*
Pattern 2	64.8	*65.7*	*65.7*	*65.7*
Pattern 3	54.9	55.8	*56.7*	*56.7*
Pattern 4	61.2	*63.9*	*63.9*	*63.9*

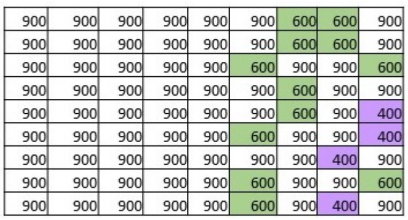


(a) GTO



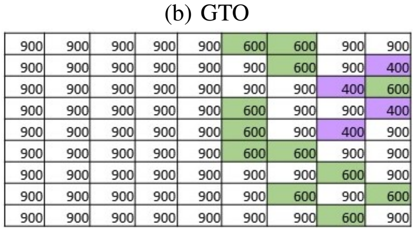
(b) BES

Fig. 2: Optimal Configurations for Pattern 1



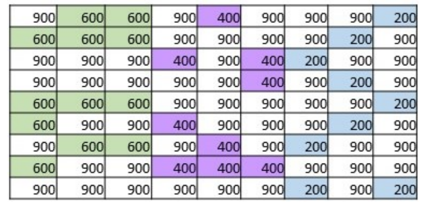
(a) MRFO

(b) GTO

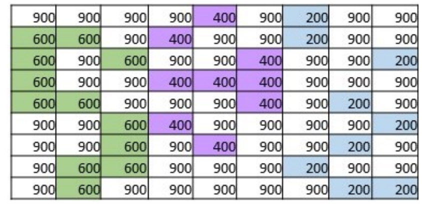


(c) BES

Fig. 3: Optimal Configurations for Pattern 2

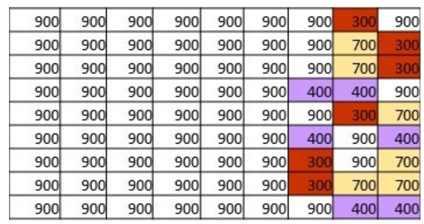


(a) GTO

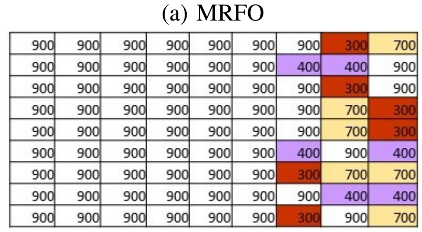


(b) BES

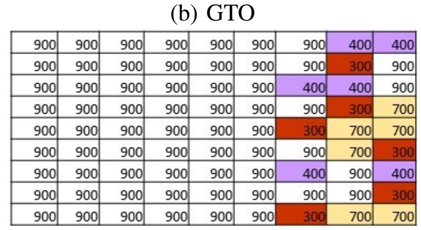
Fig. 4: Optimal Configurations for Pattern 3



(a) MRFO



(b) GTO



(c) BES

Fig. 5: Optimal Configurations for Pattern 4

In real life, however, it is quite difficult to assume that the shaded patterns appearing during PSC shall remain the same. Thus, the optimization techniques were applied to optimize the solar PV configuration for all shading patterns simultaneously.

After executing the optimization techniques for optimizing multiple shading patterns simultaneously, it was found that GTO method performed better than others. The optimal configurations obtained in the above case of simultaneous application of patterns by different optimization techniques were applied to solve individual patterns. The output power obtained for each pattern for different optimization techniques is summarized in Table II. Fig 6 presents the comparison of results obtained for individual optimization and combined simultaneous optimized configuration.

None of the methods is able to get the optimal output in simultaneous optimization as compared to individual optimization. In the second pattern, GTO and MRFO are able to achieve optimal configuration in simultaneous optimization. In the third pattern, we can observe a repetition of performance by MRFO and GTO. In fact, MRFO has improved the output as compared to individual optimization. For the fourth pattern, none of the methods are able to reach optimal configuration

TABLE II: Performance Comparison of Metaheuristic Techniques for Combined PSCs

Shaded Pattern	PSO	MRFO	GTO	BES
Pattern 1	46.8	47.7	48.6	48.6
Pattern 2	63	65.7	65.7	64.8
Pattern 3	54.8	56.7	56.7	55.8
Pattern 4	61.2	63	63	61.2

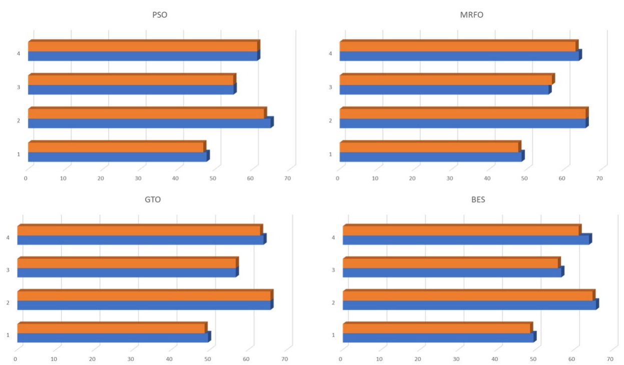


Fig. 6: Optimal Output Individual and Simultaneous Pattern Consideration

in simultaneous optimization. The convergence curve of GTO for the first 30 iterations while solving the combined PSCs is given in Fig 7.

Let us now analyze another aspect of the results. The individual patterns were optimized to obtain specific configurations. These configurations were then applied to other patterns to observe the output. Two optimization techniques obtained the optimal output for patterns 1 and 3, whereas three optimization techniques obtained the optimal output for patterns 2 and 4. These configurations were different from each other, even for the same patterns. All the optimal configurations were then applied to other patterns. The results are compiled in Tables III, IV, V, and VI.

Fig 8 presents the final comparison of different methods. This figure combines the best outputs from Table II, III, IV, V, and VI. From the figure, it can be observed that the configuration obtained for combined shaded patterns through

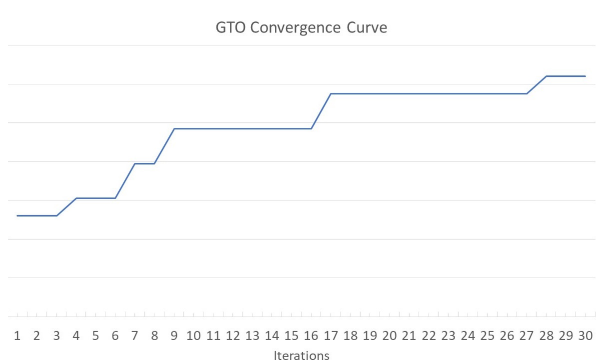


Fig. 7: GTO Convergence Curve

TABLE III: Pattern 1 Optimized PSC pattern applied to others

Shading Pattern	GTO	BES
Pattern- 1	49.5	49.5
Pattern- 2	63	63
Pattern- 3	54.9	49.5
Pattern- 4	61.2	57.6

TABLE IV: Pattern 2 Optimized PSC pattern applied to others

Shading Pattern	MRFO	GTO	BES
Pattern- 1	48.6	44.1	48.2
Pattern- 2	65.7	65.7	65.7
Pattern- 3	52.2	48.6	52.2
Pattern- 4	61.2	61.2	61.2

GTO is the best acceptable solution. It underperforms only for pattern 1; however, it gives the best results for the remaining patterns.

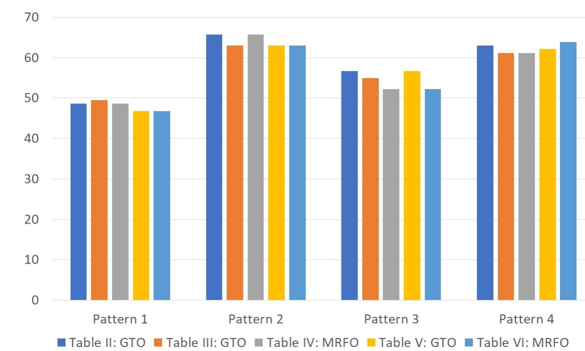


Fig. 8: Optimal Configurations Individual and Simultaneous

V. Conclusion

The solar PV configuration is very important for the optimal performance of a solar plant. There are different methods to obtain the optimal configuration. Metaheuristic methods are applied to obtain the optimal solar PV configuration in this paper. Different shaded patterns are studied and optimized individually and simultaneously. It was concluded that a solar PV configuration obtained through the simultaneous application of different shaded patterns solved through GTO gives the most acceptable solution.

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TABLE V: Pattern 3 Optimized PSC pattern applied to others

Shading Pattern	GTO	BES
Pattern- 1	46.8	46.8
Pattern- 2	63	61.2
Pattern- 3	56.7	56.7
Pattern- 4	62.1	62.1

TABLE VI: Pattern 4 Optimized PSC pattern applied to others

Shading Pattern	MRFO	GTO	BES
Pattern- 1	46.8	43.2	43.2
Pattern- 2	63	61.2	63
Pattern- 3	52.2	52.2	52.2
Pattern- 4	63.9	63.9	63.9

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