A Multi-Producer Group-Search-Optimization Method-Based Maximum-Power-Point-Tracking for Uniform and Partial Shading Condition

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This work was supported in part by the National Natural Science Foundation of China under Grant 52077189, and in part by the Natural Science Foundation of Hunan Province under Grant 2020JJ4577.

ABSTRACT The power-voltage (P-U) curve of PV array shows multiple power points, which brings challenges to fast and accurately tracking of the global maximum power point. Considering the nonlinearity and the multi-peak characteristics of PV array output curve under the condition of partial shading, a multi-producer group search optimization (MGSO) method for maximum power point tracking (MPPT) is proposed in this paper. In the MGSO, the characteristics and operations of three categories of members, including producers, scroungers, and rangers, are set according to the P-U characteristics. The number of producers is determined by the number of peaks. The initial position of each producer locates dispersedly to each peak region which makes the producers not fall into local optimum. The search strategy is simplified by the proposed angle transformation function of scroungers and omitting the ranger. The results of simulation and comparison demonstrate that the proposed MGSO method can effectively track the maximum power point under the uniform irradiance or partially shaded conditions, and also increase the utilization of solar energy.

INDEX TERMS PV utilization, group search optimization algorithm, maximum power point tracking, particle swarm optimization algorithm, photovoltaic system.

I. INTRODUCTION Photovoltaic (PV) power, as one of the key renewable energies, has attracted universal attention all over the world [1]. One of the key challenges is to improve the efficiency of PV power by tracking the maximum power point, which is the basis for improving PV utilization and prosumer energy management [2]. A series of maximum power point tracking control algorithms (such as hill-climbing [3], perturbation method [4], and observation method [5]) are proposed to improve the efficiency, which demonstrate good performance mainly under single peak condition. However, the power-voltage (P-U) curve of PV array shows multi-peak characteristic in many cases of partial shadow. The existing MPPT algorithms above mentioned are easily trapped into local extreme point [6], [7]. To address this problem, the scholars proposed some multi-peak global maximum power point tracking (GMPPT) control methods [8], including:

1. The hardware GMPPT control method based on array structure. It improves the immunity of array to partial shadow by changing the original system structure [9], [10]. The common connecting structures include simple series, series parallel and bridge link.

2. The improved direct GMPPT control method based on sample data. It pretreats the system characteristic curve to reduce the scope of global maximum power point and then uses the traditional direct MPPT control method based on sample data to track the global maximum power point [11]–[13].

3. The intelligent GMPPT control method based on the modern control theory. It includes swarm intelligence optimization algorithm [14]–[18], evolutionary algorithm [19], [20], fuzzy logic control algorithm [21], neural network control algorithm [22], [23], and double carrier chaotic search algorithm [24].
4. The GMPPT control methods based on software, such as Fibonacci linear search algorithm [25], maximum power point positioning method based on derivative equivalent area [26], voltage window scanning method [27], and so on.

According to the analysis above, the multi-peak MPPT is an urgent problem to be solved. The regularities between the array voltage and the power peak point under the condition of partial shadow have been described in [14], [17]. The regularities can be used to improve the efficiency of PV MPPT with the combination of an algorithm with good multi-peak optimization performance. The group search optimization (GSO) algorithm, proposed by S. He and Q. H. Wu etc. [28], is a heuristic algorithm which is derived from animal foraging behavior of social animals, such as birds, fish, lions and so on. The GSO algorithm shows good global search ability in several applications, especially in multi-peak function, and has good global convergence [29]–[32]. However, how to apply the GSO algorithm in combination with the performance of PV to improve the efficiency of MPPT is still rare. Therefore, a multi-producer group search optimization (MGSO) MPPT method is proposed in this paper to obtain global multi-peak optimization efficiently of GMPPT in photovoltaic energy system.

The paper is organized as follows. The characteristic analysis and regularities for proposing MGSO of PV array are presented in section 2. The MGSO algorithm with the process to solve multi-peak MPPT problem is presented and analyzed in Section 3. In Section 4, case studies and the comparison with the particle swarm optimization (PSO) algorithm are discussed, followed by conclusions.

II. THE REGULARITIES FOR PROPOSING MGSO ACCORDING TO CHARACTERISTICS OF PV ARRAY

The PV cells, which are basic modules of PV power generation, have low output voltage and small current. The PV cells are generally encapsulated into array structure by means of series connection and parallel connection. Taking the $4 \times 3$ array as an example, the PV array structure is given in Figure 1.

A $3 \times 4$ series-parallel PV array is shown in Figure 1. The substrings are in parallel, and 4 modules are in series in each branch. In order to avoid the module operating at reverse voltage, bypass diodes ($D_{S1}$, $D_{S2}$, $D_{S3}$, $D_{S4}$) are connected in anti-parallel with each module. Meanwhile, in order to prevent back current, the units need to be connected in parallel after each unit is connected in series with the blocking diodes ($D_{P1}$ and $D_{P2}$).

The parameters of SOLAREX MSX60 solar cell module are applied. The specific parameters are shown in Table 1. The reference temperature is $25^\circ$ and the reference illumination intensity is 1000 W/m$^2$.

The voltage corresponding to the extreme point of output power in PV array is important information in MPPT under partial shading condition [14]. The following two cases of shaded conditions are taken as examples to develop the characteristics of PV array under partial shading condition for proposing MGSO method.

(1) Case 1. The distributions of the shaded are [2:0:3]: the illumination intensity of 1B and 3B are 700 W/m$^2$; that of 1C and 3C are 500 W/m$^2$; that of 3D is 300 W/m$^2$; and that of the rest are 1000 W/m$^2$. The P-U curve is shown in Figure 2. From the Figure, the open circuit voltage of the array $U_{OC, array}$ is 120 V (i.e. the maximum voltage in the Figure), and the open circuit voltage of the component $U_{OC, module} = U_{OC, array} / 4= 30 V$.

(2) Case 2. The distributions of the shaded are [0:2:2]: the illumination intensity of 2C and 3C are 600 W/m$^2$; that of 2D and 3D are 300 W/m$^2$; and that of the rest are 1000 W/m$^2$. The P-U curve is shown in Figure 3. The open circuit voltage

| TABLE 1. Parameters of PV module. |
|-----------------------------------|
| $T_w=25^\circ$C(298K)             |
| Open-circuit voltage $U_{OC}$     |
| Short-circuit current $I_{SC}$    |
| Voltage in maximum power $U_m$    |
| Current in maximum power $I_m$    |
| maximum power $P_m$               |
|-----------------------------------|
| 34.2V                             |
| 9.2A                              |
| 20V                               |
| 7.95A                             |
| 159W                              |
of the array $U_{OC\_array}$ is 122V, and the open circuit voltage of the component $U_{OC\_module} = U_{OC\_array}/3 = 40.7V$.

From Figure 2, there are 4 power extreme points. In which, the extreme points $(U_1, P_1)$, $(U_2, P_2)$ and $(U_4, P_4)$ are local maximum points, and $(U_3, P_3)$ is the global maximum point. The maximum power is 864.53W. For each extreme point, the following relation between the voltage and open circuit voltage is: $U_1 = 22V \approx 1 \times k_1 \times U_{OC\_module}$; $U_2 = 44 \approx 2 \times k_1 \times U_{OC\_module}$; $U_3 = 68V \approx 3 \times k_1 \times U_{OC\_module}$; $U_4 = 93V \approx k_2 \times U_{OC\_module}$; $(k_1 = 0.7 - 0.9; k_2 = 0.75 - 0.85)$.

Form Figure 3, there are 3 power extreme points. In which, the extreme points $(U_1, P_1)$ and $(U_3, P_3)$ are local maximum points, and $(U_2, P_2)$ is the global maximum point. The maximum power is 1075.18W. For each extreme point, the following relation between the voltage and open circuit voltage is: $U_1 = 38V \approx 1 \times k_1 \times U_{OC\_module}$; $U_2 = 71V \approx 2 \times k_1 \times U_{OC\_module}$; $U_3 = 98V \approx k_2 \times U_{OC\_module}$.

From the above analyses we can obtain the following conclusions. For a $(m \times n)$ PV array, the number of peak is equal to the number of illumination type. Assuming that the types of shaded illumination in all branches are r, the number of peak points is $r+1$. The maximum numbers of peak are no more than $n+1$ under different conditions of illumination intensity. When the illumination conditions in each series branch are different, there will be $n+1$ peak points in this case. The array voltage of ith peak point should be around $k_1 \times i \times U_{OC\_module}$ ($i = 1, \ldots, r$), which lies within the range of $(i-1) \times U_{OC\_module}$ to $i \times U_{OC\_module}$. The array voltage of the r+1 peak point is about $k_2 \times U_{OC\_array}$ which is within the range of $r \times U_{OC\_module}$ to $(r+1) \times U_{OC\_module}$. of members vary from each category, but the members share information in a certain way [28], [29].

A. MGSO ALGORITHM

Multi-peak MPPT problem of PV array is a two-dimensional multi-peak problem [8]. The objective function is the maximum of output power in the array. The position of the producer, the scroungers and the rangers represent the input voltage value in the array. To track efficiently and effectively the maximum power point under the uniform irradiance or partially shaded conditions according to the regularities between the multi-peak power and its corresponding voltage, the MGSO algorithm is proposed in this paper, which includes the following aspects.

1) SETTING THE NUMBER OF PRODUCERS EQUALING TO THE NUMBER OF MULTI-PeAK IN MGSO

For the PV array with its size $m \times n$, assuming that there are $r$ different shadow conditions resulting in $r+1 (r \leq n)$ peak points. When only one producer is used to obtain the maximum among $r+1$ peak ranges, the MPPT algorithm may converge to a local maximum point and the tracking is time-consuming. If the regularities between the multi-peak power and its corresponding voltage are applied and a producer is placed in each peak range, the tracking among $r+1$ peak ranges can be conducted by $r+1$ producers in parallel. In this way, the search results of the producers can be compared to avoid falling into a local maximum point. Therefore, it is necessary to increase the number of producers and make the number of producers equal to the number of multi-peak. This setting of number of producers cannot only help to obtain all possible extreme points and improve the efficiency of the algorithm, but also help to avoid falling into the local optimum. The algorithm is named as multi-producer group search optimum (MGSO) in this paper because it includes multiple producers.

2) INITIALIZATION MODE OF THE POSITION OF THE PRODUCERS

A good initial position can not only accelerate the algorithm search speed, but also help to obtain global maximum power point. The initial positions of $r+1$ producers are set in the tracking method according to (1) by using the peak-voltage characteristics in the previous section, and the ith producer $P_{ri}$ ($1 \leq i \leq r+1$) searches within the range of $(i-1) \times U_{OC\_module}$ to $i \times U_{OC\_module}$.

$$X_{P_{r1}} = 0.7U_{OC\_module}$$
$$X_{P_{r2}} = 0.7U_{OC\_module} + k_1U_{OC\_module}$$
$$\vdots$$
$$X_{P_{rm}} = 0.7U_{OC\_module} + k_1(r-1)U_{OC\_module}$$
$$X_{P_{r(r+1)}} = k_2U_{OC\_array}$$

where $X_{P_{ri}}$ ($1 \leq i \leq r+1$) is the initial position of the ith producer; The coefficient 0.7 represents the lower limit of the range to avoid losing extreme point.
3) SEARCH STRATEGY OF THE PRODUCERS
In MGSO algorithm in the multi-peak MPPT of PV array, the power can be obtained according to the P-U relationship based on the voltage point. The \( i \)th producer \( Pr_i \) searches in the range of \((i - 1) \times U_{OC_{module}}\) to \(i \times U_{OC_{module}}\) according to the relation between the voltage and open circuit voltage of each extreme point. The search strategy of each producer can be calculated by (2).

\[
\begin{align*}
X_{i,k}^{l,k+1} &= X_{i,k}^l, \\
X_{i,k}^{l,k+1} &= X_{i,k}^l - r_1 |p_{Pr_{max}}|, \\
X_{i,k}^{l,k+1} &= X_{i,k}^l + r_1 |p_{Pr_{max}}|
\end{align*}
\]  

(2)

where \( X_{i,k}^l \) represents the position of the \( i \)th producer \( Pr_i \) at the \( k \)th iteration; \( X_{i,k}^{l,k+1}, X_{i,k}^{l,k+1} \) and \( X_{i,k}^{l,k+1} \) respectively represent the position of the \( i \)th producer \( Pr_i \) in the middle, right and left after the \( k+1 \)th iteration, \( |p_{Pr_{max}}| \) represents the maximum search distance of the producer. Considering the \( i \)th producer \( Pr_i \) searches in the range of \((i - 1) \times U_{OC_{module}}\) to \(i \times U_{OC_{module}}\), then set \( |p_{Pr_{max}}| = |U_{OC_{module}}| \) where \( r_1 \) is a random number between \((0, 1)\).

At the \( k+1 \)th iteration, the position of each producer \( X_{Pr_i}^{i,k+1} \) is the maximum in the direction of middle, right, and left, as (3):

\[
X_{Pr_i}^{i,k+1} = \max \left( X_{i,k}^{l,k+1}, X_{i,k}^{r,k+1}, X_{i,k}^{l,k+1} \right)
\]  

(3)

After obtaining the optimal position of each producer, the optimal position of this iteration can be obtained according to (4):

\[
X_{Pr_i} = \max_{1 \leq l \leq l+1} \left( X_{Pr_i}^{i,k+1} \right)
\]  

(4)

4) SEARCH STRATEGY OF SCROUNGERS
Scroungers believe that food can be found in the range between them and their producer, so they will keep searching for opportunities to join the resources found by the producer. At the \( k \)th iteration, the behavior of the \( j \)th scrounger can be modeled as a random walk toward the corresponding \( Pr_i \) producer

\[
X_{Pr_i,j}^{k} = X_{Pr_i,j}^k + r_3 \circ (X_{Pr_i}^k - X_{Pr_i,j}^k)
\]  

(5)

where \( X_{Pr_i,j}^k \) is the position of the \( j \)th scrounger corresponding \( Pr \) producer \( i \) at the \( k \)th iteration, the operator “\( \circ \)” represents the Hadamard product or Schur product, \( r_3 \) is a uniform random sequence in the range \((0, 1)\).

During scrounging, the \( j \)th scrounger will keep searching for other opportunities to become a producer when the position of this scrounger is superior to their current producer. This behavior of the scrounger is modeled by turning the \( j \)th scrounger’s head angle to a new randomly generated angle.

\[
\phi_{Pr_i,j}^{k} = \phi_{Pr_i,j}^k + r_2 \alpha_{max}
\]  

(6)

where \( \phi_{Pr_i,j}^k \) is the angle of the \( j \)th scrounger corresponding \( Pr \) producer \( i \) at the \( k \)th iteration; \( r_2 \) is a uniformly distributed random sequence in the range \((0, 1)\); \( \alpha_{max} \) is the maximum turning angle.

5) OMIT RANGERS
According to the actual characteristics of the multi-peak PV array, once the number of producers and their initial position are defined, the search results can reach a high accuracy and can be avoided falling into the local optimum. Therefore, omitting the rangers with the process that the rangers develop into the producer can improve the computational efficiency of the algorithm.

6) TERMINATION CONDITION
When the maximum power group search optimization tracking method completes the \( N \) iterations or meets the convergence conditions, the MGSO searching is terminated. At this moment, the voltage of the member whose corresponding power is the maximum one donates as \( U_m \), and the corresponding maximum power donate as \( P_m \). The specific convergence conditions are as follows:

\[
|P_k - P_{k-1}| \leq \epsilon, \quad \epsilon = 0.01
\]  

(7)

where \( P_k, P_{k-1} \) represent the maximum power of the \( k \)th and \((k - 1)\)th iteration, respectively.

7) ALGORITHM RESTART
When the output power of PV array fluctuates greatly, the MGSO algorithm needs to be restarted to search for the optimal value of the PV voltage so as to make it operate at the new maximum power point. The power change rate \( \Delta P \) is expressed by (8):

\[
\Delta P = \frac{|P_{real} - P_m|}{P_m}
\]  

(8)

where \( P_{real} \) is the real-time output power when the array operates at the maximum power point. According to the monitoring, it finds that when the light intensity changeless than 20W/m\(^2\) per minute, its corresponding array output power change rate \( \Delta P \) is 0.015. Therefore, if the light intensity and ambient temperature are stable, the power change rate would be less than 0.015. Thus, the condition of mutation restart is set as \( \Delta P > 0.015 \) in this paper.

B. THE PROCESS OF SOLVING MULTI-PEAK MPPT PROBLEM BY APPLYING MGSO
According to the above search strategy, the MGSO algorithm of process in multi-peak MPPT tracking is shown as follows.

1) Population initialization: set the maximum iterations to \( N \), generate initial population of \( r + 1 \) producers with the initial positions according to Section I.
2) Conduct the producer cycle: conduct the search cycle of the \( i \)th producer \( Pr_i \), and set the \( i \)th producer \( Pr_i \) searches at the range of \((i - 1) \times U_{OC_{module}}\) to \(i \times U_{OC_{module}}\), at this time the position of the \( i \)th producer is \( X_i^l \). The producer search strategy is conducted by (2). The scroungers search strategy toward the producer by (5).
3) Search for the position \( X_{Pr_i}^{i,k+1} \) of the \( k + 1 \)th generation producer \( i \) : obtain the position of the \( k + 1 \)th generation producer \( i \) according to (3).
4) Search for final global optimal position of the \( k + 1 \)th generation \( X_{Pr} \) : After carrying out the search cycle
of each producer’s maximum power point, the optimal value of the \( k + 1 \)th iteration can be determined according to (4).

5) Obtain the optimal value of each generation: obtain the optimal position of each generation after completing \( N \) iterations or meeting the convergence conditions.

6) Obtain the global maximum power: obtain the voltage corresponding to the global optimal position, make the PV array runs at the present array voltage point, and then obtain the present output power of the PV array.

7) Algorithm restart: when the change rate of tracking PV array output power is over 0.015, restart the algorithm search process.

IV. CASE STUDIES

A. THE SIMULATION MODEL

Taking the \( (4 \times 3) \) PV array as an example, the PV array structure is given in Figure 1, the parameters of solar cell module are shown in the Table 1. The initial temperature and illumination intensity are set as 25°C and 1000 W/m². The Boost-based MPPT PV simulation system is shown in Figure 4. The component parameters are: \( R_1 = 0.02 \Omega, R_2 = 20 \Omega, L_1 = 0.02 \text{H}, C_1 = 2000 \mu \text{F}, C_2 = 3500 \mu \text{F} \). The coefficients \( k_1 \) and \( k_2 \) in (1) are 0.8 and 0.85 respectively. The cases of this paper are simulated involving various peak numbers, illumination intensity types and temperature types as follows.

B. THE SIMULATED ANALYSIS OF UN-SHADOWED CONDITION

The illumination intensity of the PV array string and the temperature of PV module are set as 1000 W/m² and 25°C in un-shadowed condition. The \( P-U \) curve of PV array is shown in Figure 5 and the actual maximum power is 2003.50W. The tracking effect of MGSO method is shown in Figure 6. The output power of maximum power point from MGSO is 2003.41W, and the convergence time is 0.1210 s. The absolute error between output power and actual power is 0.09W, and the relative error is 0.0045%. The above results prove that the proposed MGSO method can accurately track the maximum power of PV array in un-shadowed condition.

C. THE SIMULATION ANALYSIS OF PARTIAL SHADING

1) CASE 1 OF PARTIAL SHADING

In the first condition of partial shading, the shaded distribution of PV array is \([1:0:0]\). The illumination intensity of shaded module is set as 700 W/m². Considering the different numbers of module under different illumination conditions, the numbers of shaded module in each branch are set to 1, 2 and 3 respectively. The temperature is set as the following two conditions. First, the temperatures of shaded module and unshaded module are set as 25°C. Second, the temperatures of shaded module are set as 23°C, and the unshaded module is set as 25°C. The simulation results by using MGSO method are shown in Table 2. When the number of shaded module is 2 and the temperature is 25°C, the \( P-U \) curve can be seen in Figure 7. The tracking simulation results are shown in Figure 8. Table 2 and the \( P-U \) curve prove that the proposed MGSO method can track the maximum power of PV array effectively in this condition.
2) CASE 2 OF PARTIAL SHADING

In the second condition of partial shading, the shaded distribution of PV array is [0:2:2]. The illumination intensities of shaded module are set as 600 W/m² and 300 W/m². Considering the different numbers of module under different illumination conditions, the number of shaded module in each branch are set to (1, 1), (2, 1) and (1, 2) respectively. The following two temperature conditions are considered. First, the temperatures of shaded module and unshaded module are all 25°C. Second, the temperatures of shaded module which the illumination intensities is 600 W/m² is set as 22°C and that of 300 W/m² are set as 18°C, and the unshaded module is set as 25°C. The simulation results by using MGSO method are shown in Table 3. Among the above results, when the number of substring modules are (1, 1) and the temperature is 25°C, the P-U curve is shown as Figure 9. The tracking simulation results are shown in Figure 10. Table 3 and P-U curve prove that the proposed MGSO method can track the maximum power of PV array accurately in this condition.

3) CASE 3 OF PARTIAL SHADING

The shaded distribution of PV array is [2:0:3] in the third condition of partial shading. The illumination intensities of shaded module in each branch are set as 700 W/m², 500 W/m² and 300 W/m². The structural appears as (1, 1, 1, 1). The temperature is set as the following two conditions. First, the temperatures of shaded module and unshaded module are all 25°C. Second, the temperatures of shaded module which the illumination intensities are
700 W/m², 500 W/m², 300 W/m² are set as 23°C, 22°C, 18°C respectively, and that of the unshaded module is set as 25°C. By using the GSO method, the simulation results are shown in Table 4. Among the above results, when the temperature is 25°C, the $P-U$ curve is shown as Figure 11. The tracking simulation results are shown in Figure 12. From the Table 4, Figure 11 and 12, it proves that the proposed MGSO method can track the maximum power of PV array effectively in this condition.

From the tracking results under uniform irradiance or partially shaded conditions, the relative error of all the tracking result are less than 1%. It proves that the proposed MGSO method can applicable to GMPPT in different kinds of illumination intensity and temperature. The convergence times of all condition are nearby 0.15s. Furthermore, it can be seen that the MGSO method with good convergence stability can search the maximum power point effectively.

D. COMPARISON WITH THE EXISTING METHODS

1) COMPARISON OF MGSO AND PARTICLE SWARM OPTIMIZATION (PSO) IN MPPT

To verify the feasibility of proposed MGSO method, the MGSO method is compared with the typical and popular PSO method which is very effective to handle the multimodal power voltage(P-V) curve under partial shading conditions [17], [18], [30]. From the simulations, the data such as power, the absolute error, relative error and convergence time, and efficiency are tabulated in Table 5. The simulation parameters of MGSO and PSO are set as the same conditions in the above mention. The comparison results are given in Table 5.

From Table 5, the absolute error, relative error and convergence time at different number of peaks in MGSO are better than that in PSO method. The comparisons from absolute/relative errors prove that the MGSO method can search the maximum power point more accurately. With the number of peaks increasing, the running and convergence time of MGSO algorithm increases slowly. The MGSO algorithm can search the maximum power point of PV array more quickly.

2) COMPARISON OF TRACKING EFFICIENCY WITH THE MAIN EXISTING METHODS

To verify the effectiveness of the proposed MGSO method, the main existing methods, such as PSO algorithm, deterministic particle swarm optimization (DPSO) algorithm [17], sliding mode variable structure control (SMVSC) method and perturbation and observation (P&O) method [33] are used.
for comparison. The efficiencies of MGSO and PSO are the average tracking efficiency from Table 5, and those of others are available from the literature results. The comparisons are given in Table 6.

From the comparisons in Table 6, the proposed MGSO has better tracking efficiency than other methods. The MGSO arithmetic is simple, fast, effective and efficient, which is suitable for the MPPT of PV arrays considering partial shading.

V. CONCLUSION

In this paper, the MGSO method is proposed to track the maximum power point of a PV system. The MGSO could guarantee the method not fall into local optimum by increasing the number of producer and locating the initial position of the producers. To improve the accuracy and efficiency, the tracking method simplifies the search strategy and omitting the ranger. According to the simulation results, the MGSO algorithm in MPPT can quickly and accurately track the maximum power point under single-peak and multi-peak condition. Comparing with the PSO from error, convergence time and efficiency and comparing with the main existing algorithms from tracking efficiency in MPPT, the MGSO algorithm has good optimization effect, optimization accuracy and higher efficiency, and can also avoid falling into local optimum. To sum up, the proposed MGSO algorithm is feasible to provide application conditions for MPPT.

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