Optimal Photovoltaic Array Dynamic Reconfiguration Strategy Based on Direct Power Evaluation

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ABSTRACT In actual operation, photovoltaic arrays inevitably encounter shadow problems, resulting in a power output decline and multiple peaks in the output characteristics. The effect of partial shade can be satisfactorily reduced by photovoltaic array reconfiguration. Almost all current reconfiguration techniques are based on the irradiance equalization principle. However, by analyzing the output characteristics of photovoltaic array, it is found that the irradiance equalization principle improves the output power by increasing only the minimum row current without considering the effect of the voltage, so the reconfiguration techniques based on this principle cannot obtain the global optimal configuration under some partial shading conditions. In order to maximize the output power of photovoltaic array under any partial shaded condition, this paper proposes a reconfiguration strategy based on direct power evaluation. In this approach, the reconfiguration problem is formulated as a 0-1 multi-knapsack problem, and a novel mathematical model is established to directly evaluate the maximum output power of photovoltaic array. Then, the optimal reconfiguration scheme is determined by solving the mathematical model. Finally, the effectiveness of the proposed reconfiguration strategy is proved in theory and simulations.

INDEX TERMS PV reconfiguration, partial shading, irradiance equalization, output characteristics, optimization.

I. INTRODUCTION
Typically, photovoltaic (PV) modules are connected in series and parallel to form a PV array [1]. In actual operation, due to the influence of clouds, buildings and other factors, some PV modules will inevitably receive lower irradiance, which will lead to changes in their electrical characteristics. The difference in electrical characteristics between PV modules will greatly reduce the output power of the entire PV array and cause local hot spots [2]. Bypass diodes are usually connected across each PV module to protect it from damage; however, this introduces multiple peaks in the P-V characteristics of a PV array [3]–[5].

The power loss caused by partial shading is not only related to the shading conditions but also to the interconnection mode of a PV array [6]; among these modes, series-parallel (SP), total-cross-tied (TCT), and bridge-linked (BL) are the most common [7]. It has been found that the TCT topology can minimize mismatch losses and increase reliability better than other configurations [8], [9]. However, despite reducing the mismatch loss to a certain extent, these interconnection schemes still fail to maximize the output power. In order to compensate the power loss more effectively, researchers have proposed a method of PV array reconfiguration, which reconfigures the PV modules within the PV array according to the actual shadow conditions, so as to increase the maximum power to a higher level and minimize the influence of mismatch.

In the reconfiguration strategy of the TCT topology, the widely adopted idea of “irradiance equalization” was proposed in [10]–[12]. Irradiance equalization aims to obtain series-connected rows, where the sum of the irradiiances of the modules is almost equal [13]. In other words, its basic idea is to minimize the difference between the row currents so that none of them will limit the current of the entire PV array. Thus, uniform shade dispersion is achieved to increase the output power of the PV array under partial shaded conditions. The current techniques for PV array reconfiguration
utilizing the irradiance equalization principle are extensively summarized in [14], [15], in which they are divided into static and dynamic reconfiguration techniques.

The authors of [6], [16]–[19] proposed several static reconfiguration techniques. In these techniques, the physical location of the PV modules in TCT topology is changed according to SuDoKu and other arrangements to distribute partial shading effects over the array. Compared with dynamic reconfiguration techniques, static reconfiguration techniques can save a large number of switches and do not require any sensors. However, they cannot adaptively find the optimal interconnection scheme under changes in the irradiance conditions, since the interconnection scheme is fixed.

In dynamic reconfiguration techniques, the physical location of the modules in the PV array remain unchanged, and shade dispersion is achieved by dynamically changing the electrical interconnections of the PV modules. In [11], the concept of “equalization index” was proposed, which quantifies the level of irradiance equalization. The optimal configuration is the one that minimizes the equalization index. A variation of this technique was proposed in [20], which can be applied when a non-equal number of modules per row is considered. In these techniques, the exhaustive algorithm or the branch and bound algorithm is used to solve the mathematical model. However, as the scale of PV array increases, the complexity of the problem will increase dramatically, and the optimal solution may not be obtained within an acceptable time. Therefore, increasing numbers of researchers have applied heuristic algorithms such as the genetic algorithm (GA) [21], particle swarm optimization algorithm (PSO) [22], grasshopper optimization algorithm (GOA) [23], social mimic optimization algorithm (SMO) and Rao optimization algorithm [24] to PV array reconfiguration. Since the above reconfiguration techniques establish appropriate mathematical models for irradiance equalization, they can balance the irradiance of PV modules in each row to the greatest feasible extent, but their large computational burdens are the main problem. Therefore, in [25], an iterative and hierarchical sorting method was proposed for achieving a nearly optimal irradiance equalization configuration. Similar approaches were presented in [26], [27]. These techniques use the idea of shade dispersion in the irradiance equalization principle to distribute the shading effects in each row as evenly as possible according to certain rules. Since there is no need to build and solve mathematical models for irradiance equalization, these techniques are relatively simple, but they cannot guarantee that an optimal balance of irradiance will be achieved. Another technique, called adaptive reconfiguration was presented in [28]–[30]. It consists of a fixed part and an adaptive part. The basic idea of this technique is to connect the most illuminated modules in the adaptive part to the most shaded row of the fixed part, so that the illumination levels of each row is approximately equal. The adaptive part still obeys the irradiance equalization principle.

In summary, although the specific implementation methods and processes differ, almost all current reconfiguration techniques are based on the irradiance equalization principle, and they achieve a fairly uniform shade dispersion. However, by analyzing the essence of the irradiance equalization principle, it is found that this principle improves the output power only by increasing the minimum row current and does not consider the effect of voltage. Therefore, the reconfiguration techniques based on the irradiance equalization principle cannot optimize the global optimal configuration of a PV array under some partial shaded conditions, and the output power of the PV array can be further improved.

On the other hand, the ultimate goal of the reconfiguration is to maximize the output power of the PV array. The existing reconfiguration methods, however, still cannot give a direct calculation method for the global maximum power of a PV array under partial shaded conditions, so they cannot use any direct information about the maximum output power, which is unreasonable for optimal PV array reconfiguration. Therefore, it is necessary to analyze the output characteristics of PV array under partial shaded conditions to evaluate the maximum output power.

In this paper, a reconfiguration strategy based on direct power evaluation is proposed. Based on the analysis of the output characteristics of the PV array under partial shading conditions, this paper reveals the problems of the existing reconfiguration strategy based on the irradiance equalization principle. It also formulates the reconfiguration problem as a 0-1 multi-knapsack problem and establishes a new mathematical model for optimal PV array reconfiguration from the perspective of directly evaluating the maximum output power of PV array, which maximizes the output power of the PV array under any partial shaded conditions.

The paper is organized as follows: In Section II, the output characteristics of TCT interconnected PV array under partially shaded conditions are analyzed. In Section III, the essence and problems of the irradiance equalization principle are described in detail. In Section IV, a novel mathematical model for direct power evaluation is established, and the superiority of the proposed reconfiguration strategy is discussed. In Section V, the effectiveness of the proposed reconfiguration scheme under different partial shading conditions is verified by simulation. The conclusion is presented in Section VI.

II. OUTPUT CHARACTERISTICS OF TCT CONFIGURED PV ARRAY UNDER PARTIAL SHADOWED CONDITIONS

In the TCT configuration, the modules in a row are connected in parallel and those in a column are connected in series. The circuit of an $M \times N$ TCT configuration is shown in Fig. 1. For convenience, an individual PV module’s location is tagged with “$ij$”, where $i$ and $j$ represent the row and column numbers in which the module is connected, respectively. The irradiance of each module is labeled $G_{ij}$, representing the irradiance of the PV module in row $i$ and column $j$. 
Since the current at the maximum power point of a PV module is directly proportional to its irradiance and the modules in each row are connected in parallel, the current limit of each row is proportional to the sum of the irradiance values of all modules in the row. We define $G_{Ri}$ as the total irradiance of the $i$th row:

$$G_{Ri} = \sum_{j=1}^{n} G_{ij}, \quad i = 1 \ldots M$$  \hspace{1cm} (1)

Hence the current limit of the $i$th row, $I_{Ri}$, can be calculated as:

$$I_{Ri} = \frac{G_{Ri}}{G_0} I_m, \quad i = 1 \ldots M$$  \hspace{1cm} (2)

where $G_0$ is the standard irradiance (1000W/m$^2$) and $I_m$ is the current at the maximum power point of the PV module under standard irradiation conditions. Since the current flowing through the entire PV array is the same at any time, as the load current requirement increases, the rows that cannot reach higher current values will be bypassed by the diode to protect them from damage. Assume that there are $s$ different total irradiances, and sort them from large to small according to the order in which each row is bypassed:

$$G_1 > G_2 > \ldots > G_s, \quad s = 1 \ldots s$$  \hspace{1cm} (3)

The subscript $x$ here represents the serial number, and the number of rows with total irradiance $G_x$ is $m_x$, which satisfies the following relationship:

$$\sum_{x=1}^{s} m_x = M$$  \hspace{1cm} (4)

When any row of the PV array is bypassed, the output voltage will drop to a lower level, resulting in multiple peaks in the output characteristics of PV array. Therefore, the P-V curve has a total of $s$ power peaks, and the voltage, current and power of each power peak point of the TCT interconnected PV array can be approximately determined by (5)-(7):

$$V_{mx} = \left( \sum_{l=1}^{x} m_l \right) V_m$$  \hspace{1cm} (5)

$$I_{mx} = \frac{G_x}{G_0} I_m$$  \hspace{1cm} (6)

$$P_{mx} = V_{mx} I_{mx} = \left( \sum_{l=1}^{x} m_l \right) \frac{G_x}{G_0} V_m I_m$$  \hspace{1cm} (7)

where $V_{mx}$, $I_{mx}$, and $P_{mx}$ represent the voltage, current, and power at the $x$th power peak point of the TCT topology, respectively, and $V_m$ is the voltage at the maximum power point of the PV module under standard irradiation conditions. Therefore, relationships between the maximum power of the TCT topology and the irradiance parameters can be built. With these relationships, the essence and problems of the irradiance equalization principle will be discussed in detail in the next section.

### III. PROBLEMS FOR RECONFIGURATION STRATEGIES BASED ON THE PRINCIPLE OF IRRADIANCE EQUALIZATION

#### A. ESSENCE OF THE IRRADIANCE EQUALIZATION PRINCIPLE

The core idea of irradiance equalization is to achieve a uniform distribution of shade over the whole array. Specifically, irradiance equalization is the process of switching the most illuminated PV modules to the most shaded row so that the total irradiance of each row is almost equal. From the perspective of the mathematical description, irradiance equalization actually minimizes the row current difference. Many formulas for irradiance equalization have been proposed in the literature.

An optimization algorithm based on the equalization index ($EI$) was presented in [10]–[12]. This index is defined to quantify the difference in the average irradiances present in each row. For each configuration, the algorithm calculates the equalization index using the following expression:

$$EI = \max (G_{Ri}) - \min (G_{Ri}) \forall i$$  \hspace{1cm} (8)

It is worth noting that the better the irradiance equalization is, the lower the index value. Therefore, the algorithm chooses the configuration that minimizes $EI$.

Reference [20] proposed a similar mathematical index, the irradiance level mismatch index ($IMI$), to minimize all differences between the levels of the row irradiance. $IMI$ is defined as the sum of the squares of the differences between the normalized total irradiance levels of the rows, and it is given by:

$$IMI = 0.5 \sum_{i=1}^{m} \sum_{l=1}^{m} (G_{Ri} - G_{Rl})^2$$  \hspace{1cm} (9)

where $G_{Ri}$ and $G_{Rl}$ are the total irradiance levels of rows $i$ and $l$, respectively. Its objective is to reconfigure the modules in such a way that IMI is minimized.
Similar formulations were also proposed in [21]–[24], and their mathematical models all include:

\[ W_e / E_e \] (10)

where \( W_e \) is the weight factor for \( E_e \); \( E_e \) is the sum of the error difference between maximum row current in PV array and individual row current of the same, and it can be represented as:

\[ E_e = \sum_{i=1}^{M} |I_{R_{\text{max}} \text{-} i} - I_{R_{\text{i}}}| \] (11)

where \( I_{R_{\text{max}}} \) is the maximum value of row current. In fact, these mathematical formulations use concepts such as range and variance to reflect the degree of difference between row currents, thereby transforming the irradiance equalization principle into a specific mathematical problem.

According to the analysis of the output characteristics of TCT configuration in the previous chapter, the output power of PV array is the product of the output voltage and the output current, where the output voltage is dependent on the number of modules participating in power generation and the output current is limited by the minimum current of the non-bypass rows in the PV array. Hence, if all the modules in the PV array are involved in generating electricity without being bypassed, the PV array can work at the maximum voltage, which is the output voltage at the power peak of the PV array when \( x \) in (5) is equal to \( s \), and it is defined as \( V_{ms} \):

\[ V_{ms} = M \times V_m \] (12)

In this case, the output current is the only factor that limits the output power of the PV array. In order to maximize the output power of the PV array when the output voltage is equal to \( V_{ms} \), the minimum row current of the PV array should be increased as much as possible, which can be expressed as:

\[ \text{Maximize} \ [\text{min} (I_{R_{i}})] \quad \forall i \] (13)

In fact, this is consistent with (8), (9) and (10). By dispersing the shadows, the difference between row currents is minimized, thereby maximizing the minimum row current to increase the output power of the PV array and allowing as many PV modules as possible to participate in power generation without being bypassed; this is the essence of irradiance equalization.

### B. PROBLEMS OF THE IRRADIANCE EQUALIZATION PRINCIPLE

Irradiance equalization based-reconfiguration techniques can effectively improve the output power of a PV array under many partial shading conditions. However, in some cases, especially when the irradiance of individual modules differs greatly, it is possible that no matter how the PV modules are rearranged, a uniform row current cannot be obtained. In this case, the irradiance equalization strategy may no longer be optimal, and it may even cause the maximum output power of the reconfigured PV array to decrease.

Taking a 3 × 2 PV array as an example, the initial shading pattern before shade dispersion is shown in Fig. 2(a). The two modules with the lowest level of irradiation are placed in the same row of the array. According to the irradiance equalization principle, the shadows should be dispersed as evenly as possible, and the reconfigured shading pattern is shown in Fig. 2(b). Fig. 3 shows the P-V and I-V curves of the PV array under the above two shading patterns.

The degree of difference between the row currents of the two configurations can be estimated according to (8), and the results are given by:

\[ EI_a = (900 + 800) - (100 + 100) = 1500 \] (14)

\[ EI_b = (800 + 800) - (900 + 100) = 600 \] (15)

where \( EI_a \) and \( EI_b \) represent the equalization index of the two configurations before and after reconfiguration, respectively.

It is clear that the irradiance equalization-based reconfiguration scheme reduces the difference between row irradiances and achieves a more uniform shade dispersion. However, it can be seen from the P-V curve that the maximum output power of the reconfigured PV array is smaller than that before reconfiguration. In fact, it can be seen from the I-V curve that although the voltage at the maximum power point of the PV array is increased after reconfiguration, the output current decreases. For the PV array before reconfiguration, although the modules with lower irradiance are bypassed by diodes and the output voltage at the maximum power point is reduced, the remaining PV modules can provide a greater output current. This is why the maximum output power of the PV array is reduced after reconfiguration based on the irradiance equalization principle.

In summary, the irradiance equalization principle actually only maximizes the minimum row current of PV array, and this does not ensure that the output power can be maximized under all partial shaded conditions. Therefore, the irradiance.
equalization principle is not the best strategy to maximize the output power of PV arrays.

IV. DIRECT POWER EVALUATION BASED OPTIMAL PV ARRAY RECONFIGURATION STRATEGY

A. ESTABLISHMENT OF MATHEMATICAL MODEL FOR THE RECONFIGURATION PROBLEM

The reconfiguration strategy proposed in this paper is to directly evaluate the maximum output power of the PV array and find the configuration that maximizes it. However, for larger PV arrays, the number of possible configurations is very large, so it is difficult to find the optimal configuration quickly. Therefore, this paper formulates the reconfiguration problem as a 0-1 multi-knapsack problem, and the mathematical model of the reconfiguration problem can be established by analogy with the concept of the 0-1 multi-knapsack problem. So, it is necessary to determine the correspondence between the PV array reconfiguration and the 0-1 multi-knapsack problem.

The 0-1 multi-knapsack problem has two important elements, knapsacks and items, which correspond to the rows of the PV array and the PV modules. The process of putting items into the knapsack in the 0-1 multi-knapsack problem corresponds exactly to the process of putting PV modules into a row of the PV array in the control problem of the PV array reconfiguration. Therefore, the number of PV modules in each row of PV array, the irradiance of each PV module and the number of PV modules in each position of the array can be regarded as the capacity of the knapsack, the value of the item and the weight of the item, respectively.

In this way, for an \( M \times N \) PV array, the control problem of optimal reconfiguration can be described as follows: Given \( M \times N \) items and \( M \) knapsacks, each item has a weight of 1 and a value of \( k_1, k_2, \ldots, k_p \ldots k_{M+N} \), and each knapsack has a capacity of \( N \). The goal is to find \( M \) disjoint subsets of the \( M \times N \) items, where each has \( N \) items, and put them in \( M \) knapsacks to obtain the configuration that maximizes the output power.

To determine the optimal interconnection between the modules and maximize the output power of the PV array under all partial shaded conditions, we can directly use the maximum output power of the PV array as the control target. Combined with the mathematical model of the 0-1 multi-knapsack problem and the analysis in Chapter 2, the current limit of the \( i \)th row can be calculated by (16):

\[
I_{Ri} = \sum_{p=1}^{M \times N} k_p x_{pi} I_m, \quad i = 1 \ldots M \tag{16}
\]

\[
x_{pi} = 0 \text{ or } 1, \quad i = 1, 2, \ldots, M \tag{17}
\]

where \( k_p \) represents the illumination coefficient of module \( p \) and \( x_{pi} \) is a binary variable that indicates whether module \( p \) is in the \( i \)th row of the PV array; if so, then \( x_{pi} = 1 \), and otherwise, \( x_{pi} = 0 \). Then, we sort the current limits from large to small, \( I_1 > I_2 > \ldots > I_s \), and we find all possible peaks of the PV array under different shadow patterns via (7), where the largest value \( P_m \) is selected as the objective index. A mathematical model of the direct power evaluation-based reconfiguration strategy is given below. The objective function and constraints are shown in (18)-(20).

\[
\text{Maximize} \quad (P_m = \max (P_{mx})) \tag{18}
\]
Equations (19) and (20) indicate that each row consists of \( N \) PV modules and that each module can only be placed in one row. Therefore, based on the concept of the 0-1 multi-knapsack problem, a new mathematical model for the optimal PV array reconfiguration is established. The optimal reconfiguration scheme can be determined by solving the proposed mathematical model. It is worth noting that although the irradiance conditions of a PV array usually change dynamically due to the movement of the sun, this change is usually slow and exhibits a certain regularity. Therefore, it is possible to select several specific time points in a day at which to reconfigure the PV array.

Additionally, the practical implementation of reconfiguration technology requires the help of a monitoring system, a switching matrix and other devices. Although the practical implementation of reconfiguration technology is a challenging task deserving further research, it is beyond the scope of this paper. Our aim is to determine the optimal reconfiguration scheme to maximize the output power of a PV array.

**B. THE EFFECTIVENESS OF THE PROPOSED STRATEGY UNDER ALL PARTIAL SHADOW CONDITIONS**

From the perspective of actual operation, the irradiance equalization principle aims to make as many PV modules as possible participate in power generation without being bypassed by diodes. However, according to the previous analysis and verification, if some modules with a lower irradiance are bypassed and do not participate in power generation, it is possible to obtain greater output power. The proposed direct power evaluation-based reconfiguration strategy considers all operating conditions, so it can ensure that it will find the global optimal configuration by solving the proposed mathematical model.

From the perspective of the mathematical model, the irradiance equalization principle aims to increase the maximum output power by increasing the minimum row current of the PV array, while the reconfiguration strategy proposed in this paper aims to find the optimal configuration by directly evaluating the power generated by the PV array. It should be further noted that the irradiance equalization strategy considers only the currents, while the proposed mathematical model considers both the voltages and currents. Therefore, the irradiance equalization principle can be regarded as a special case of the proposed direct power evaluation-based reconfiguration strategy, and the proposed strategy can produce a maximum output power greater than or equal to that obtained by the reconfiguration scheme based on irradiance equalization. The above conclusion can be expressed by (21):

\[
P_{m-DPE} \geq P_{m-IE}
\]

where \( P_{m-DPE} \) and \( P_{m-IE} \) are the maximum output power obtained by the proposed reconfiguration strategy based on direct power evaluation and by the traditional reconfiguration strategy based on the irradiance equalization principle, respectively. When the voltage at the global maximum power point (GMPP) of the reconfigured PV array obtained by the direct power evaluation-based reconfiguration strategy is equal to \( M^*V_m \), the equality in (21) holds. If not, the resulting configuration is superior to the irradiance equalization scheme in terms of the maximum power output.

In addition, since the voltage at the GMPP of the reconfigured PV array can also be obtained in the process of solving the proposed mathematical model to determine the optimal configuration, the proposed strategy can track the GMPP directly without scanning all or part of the voltage range, thereby greatly reducing the difficulty of multi-peak maximum power point tracking (MPPT) technology.

**V. RESULTS AND DISCUSSION**

To investigate the performance of the proposed method and compare it with the irradiance equalization (IE)-based reconfiguration scheme, a simulation system is built in the MATLAB/Simulink environment. The parameters of the PV module used in the analysis are given in Table 1.

It worth explaining that in the simulation, the most ideal IE scheme is compared with the proposed scheme. Since all the published methods are based on the IE principle and their mathematical models are similar, the most ideal IE scheme can be obtained by any one of these methods under the premise of ignoring the differences in the computational abilities of the algorithms.

**A. CASE 1: THE NUMBER OF SHADED PV MODULES IS SMALL**

In this situation, a \( 6 \times 3 \) PV array is divided into three groups. The initial shading pattern is shown in Fig. 5(a). According to the IE principle, the difference between row currents should be minimized as much as possible, and the reconfigured shading pattern is shown in Fig. 5(b), while the result of the proposed direct power evaluation-based reconfiguration scheme is given in Fig. 5(c).

Fig.6 shows the P-V characteristics of the PV array obtained by the proposed scheme in comparison with other
When the IE-based reconfiguration scheme operates at the maximum power point B, all the PV modules in the array participate in power generation, and the voltage, current and power of the power peak point B can be calculated by (22)-(24):

\[
V_B = 6V_m \tag{22}
\]

\[
I_B = (1 + 1 + 0.1)I_m = 2.1I_m \tag{23}
\]

\[
P_B = V_BI_B = 6V_m \times 2.1I_m = 12.6V_mI_m \tag{24}
\]

When the proposed reconfiguration strategy operates at the maximum power point A, the last row of the PV array will be bypassed by diode, and only PV modules with irradiances of 1000 W/m² and 900 W/m² will participate in power generation. Similarly, we can calculate the voltage, current and power of the power peak point A:

\[
V_A = 5V_m \tag{25}
\]

\[
I_A = (1 + 1 + 0.9)I_m = 2.9I_m \tag{26}
\]

\[
P_A = V_AI_A = 5V_m \times 2.9I_m = 14.5V_mI_m \tag{27}
\]

The individual row current limits and the respective powers after bypassing are summarized in Table 2. It is clear from the results that in the IE-based reconfiguration scheme, the row currents range from 2.1I_m to 2.9I_m, while in the proposed scheme, the row currents range from 0.3I_m to 3I_m, which means that the IE-based reconfiguration scheme has a higher minimum row current and achieves a more uniform shade dispersion.

However, according to the above theoretical calculation results, the maximum power value of the proposed direct power evaluation-based reconfiguration strategy can reach 14.5V_mI_m, while the IE-based reconfiguration scheme only manages to produce 12.6V_mI_m. In addition, according to the simulation results, the power output using the proposed scheme is 2498W, which is 23.2% higher than the initial TCT power of 2027W and 11.2% higher than the IE scheme power of 2246W.

Therefore, although the IE-based reconfiguration scheme indirectly increases the output power by increasing the minimum row current, it cannot find the configuration that maximizes the output power globally. In contrast, for the proposed direct power evaluation-based reconfiguration strategy, although the minimum row current is only 0.3I_m, it directly aims to maximize the output power of the PV array, so it can find the global optimal reconfiguration scheme.

**B. CASE 2: THE NUMBER OF SHADEd PV MODULES IS MODERATE**

In this pattern, half of the PV modules are shaded, and the initial shading pattern is as shown in Fig. 7(a). Fig. 7(b) shows the irradiance equalization-based reconfiguration scheme, and the proposed direct power evaluation-based reconfiguration scheme is shown in Fig. 7(c). The P-V curves that correspond to TCT, IE and the proposed scheme are shown in Fig. 8.

In this case, the maximum output power using the proposed scheme is 1708 W and that for the initial TCT and the IE-based configurations are 1280 W and 1458 W. Therefore, the output power generated using the proposed reconfiguration scheme is 33.4% and 17.1% higher than that of the initial TCT configuration and the IE-based configuration, respectively.

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**TABLE 2. Location of GP in the IE and proposed arrangements.**

| Row current in the order in which panels are bypassed | Voltage (V_m) | Power (W) | Row current in the order in which panels are bypassed | Voltage (V_m) | Power (W) |
|-----------------------------------------------------|---------------|-----------|-----------------------------------------------------|---------------|-----------|
| 1R2 2.1I_m 6 12.6 | 1R6 0.3I_m 6 1.8 |
| 1R4 - - - | 1R4 - - - |
| 1R1 2.9I_m 3 8.7 | 1R3 - - - |
| 1R3 - - - | 1R2 3I_m 2 6 |
| 1R5 - - - | 1R1 - - - |

The P-V characteristics for TCT, IE and the proposed arrangement.
C. CASE 3: THE NUMBER OF SHADED PV MODULES IS LARGE

In this situation, more than half of the PV modules in the PV array are shaded. The initial shading pattern and its reconfiguration scheme based on the IE principle and the proposed strategy are shown in Fig. 9(a)-(c), respectively.

The P-V curves that correspond to TCT, IE and the proposed scheme are shown in Fig. 10. The global maximum power obtained by the proposed strategy is observed as 1692 W whereas, initial TCT and IE-based reconfiguration schemes produce a global maximum power of 1438 W and 1474 W, respectively.

D. CASE 4: THE ENTIRE PV ARRAY IS SHADED

In this situation, all PV modules are in shaded conditions. The initial shading pattern and its reconfiguration scheme based on the IE principle and the proposed strategy are shown in Fig. 11(a)-(c), respectively.

The P-V curves that correspond to TCT, IE and the proposed scheme are shown in Fig. 12. In this case, the maximum output power using the proposed scheme is 1534 W, and that of the initial TCT and the IE-based configuration is 1238 W and 1415 W, respectively. Therefore, the output power generated using the proposed reconfiguration scheme is 23.91% and 8.41% higher than that of the initial TCT configuration and the IE-based configuration, respectively.
In conclusion, the proposed reconfiguration scheme can effectively increase the maximum output power of PV array, and a noteworthy power increase of over 10% is seen in the above four cases compared to the initial TCT configuration and the IE-based reconfiguration scheme. In addition, through extensive simulations, it is verified that for different sizes of PV arrays and different shading patterns, the maximum output power of the proposed strategy is always greater than or equal to that obtained based on the IE principle.

VI. CONCLUSION

This paper proposes a novel PV array reconfiguration strategy based on direct power evaluation to maximize the global maximum output power of TCT topology under partial shading conditions. Unlike the current techniques based on the IE principle, which improve the output power by increasing only the minimum row current, the proposed strategy establishes a novel mathematical model for optimal PV array reconfiguration from the perspective of directly evaluating the maximum output power of the PV array. It is proved theoretically that the proposed strategy can overcome the problems of the irradiance equalization principle and further increase the output power of the PV array. The performance of the proposed strategy has also been verified in the MATLAB/Simulink environment. The results show that the global maximum power of the proposed strategy is much higher than that of the TCT configuration and the IE-based techniques.

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