An Algorithm for Enhanced Performance of Photovoltaic Array Under Partial Shading Condition

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ABSTRACT The partial shading on photovoltaic (PV) modules causes a reduction in generated power and multiple peak points in their electrical characteristics. If the number of shaded modules of two or more rows are different then electrical characteristics exhibit multiple peaks. Also, as the number of shaded modules in a row increases the generated power decreases. These two observations are the main idea of this paper. The algorithm proposed in this paper redistributes shaded modules to various rows such that each row gets the lowest possible number of shaded modules and thereby increases the generated power. This work discusses a condition to achieve an equal number of shaded modules in all rows for which there is only one peak in the electrical characteristics. For the case where this condition is not satisfied, there can only be two-row groups with a different number of shaded modules. However, each group is having the same number of shaded modules and so only two peaks in the electrical characteristics. The proposed algorithm is applicable to any mxn structure of PV arrays. Extensive simulations are carried out and the performance of the proposed algorithm is compared with existing methods for various shading patterns. The results show that the proposed method gives minimum power loss, better performance ratio, and a lesser number of peak points.

INDEX TERMS Maximum power generated, partial shading loss, performance ratio, reconfiguration, total cross tied configuration.

I. INTRODUCTION
Solar photovoltaic systems are becoming more popular due to its environmental friendly capabilities, reduced cost, maintenance free characteristics and renewing capability [1]. The performance of PV arrays depends upon irradiation level and the temperature [2]. The phenomena of blocking all or part of direct sun radiation on the PV modules is known as partial shading. The shades are caused by clouds, snow, dust, dirt, bird droppings, and nearby buildings [3], [4]. Partial shading on PV array causes reduction in generated power and can increase the number of maximum power points in power-voltage (P-V) characteristics [5]. Partial shading losses depend on shading pattern, array configuration, and location of the shaded modules [6]. Various methods like series (S), parallel (P), series parallel (SP), bridge link (BL), honey comb (HC) and total cross tied (TCT) are discussed in literature for the interconnections of PV arrays [7]. Among the basic PV array configurations, TCT configuration performs well for almost all shading pattern and improve the lifespan of PV array [8].

It is established in [9] that the number of shaded modules in a row greatly influence the power loss of PV array under partial shading. Various methods are presented in literature to rearrange shaded modules such that the number of shaded modules are redistributed among various rows to reduce power loss and thereby to improve the generated power. A Su-Do-Ku (SDK) puzzle based TCT arrangement is presented in [10] to improve the generated power under partial shading condition. This particular method is modified to optimal SDK arrangement for easy wiring [11]. Both the SDK methods are applicable only for a 9 × 9 PV array. Another approach is the novel structure (NS) presented in [12], where the performance under partial shading is compared with hybrid configurations and observed that NS configuration gives higher values of fill-factor and reduction...
in power loss for specific shading patterns. In [13], a magic square puzzle based reconfiguration for 4 × 4 PV array is demonstrated and its performance is compared with basic TCT configuration and rearranged hybrid configuration. These methods [10]–[13] are applicable only for the cases with equal number of rows and columns. A zig zag physical rearrangement for reducing the shading effects in PV array is developed and applied on 4 × 3 PV array for performance analysis. This particular method is theoretically compared for its competence with TCT configuration [14]. However, this method fails when the number of rows are less than the number of columns [15]. A PSO (Particle swarm optimization) based reconfiguration method is presented in [16] to improve the power generation during partial shading. However, this method is verified only for even number of rows and columns. A column index method with single time physical relocation of PV panels with simple wiring techniques is presented and performance results are compared with existing methods [17]. Latin square-TCT (LS-TCT) is a method based on the Latin square puzzle which can be applied only for 4 × 4 PV array to disperse the shades and improve the power output [18]. A permanent arrangement of PV array for reducing partial shading losses by arranging PV panels in odd even structure is presented in [19]. Authors of [20] presented an improved SDK method which is capable of enhancing power generation of partially shaded PV array. However, this strategy is acceptable only for 9 × 9 PV array configuration. The SD-PAR (static shade dispersion physical array relocation) method is presented in [21] to reduce the partial shading losses which is implemented only for a 3 × 3 PV array. An improved SDK method and arrow SDK method to reduce the partial shading losses with reduced wiring loss is presented in [22] and [23], respectively. However, competence of these methods is proved only for defined shading patterns. The image processing technique ‘chaotic baker map’ is applied in [24] to reduce the power losses of partially shaded PV arrays. This method is verified only for 4 × 4 and 6 × 6 configurations. The work proposed in [25] achieved improvement in the generated power by injecting a current corresponding to mismatch loss. This method requires an additional current source. A square matrix (SM) based shade dispersion methodology [26], a novel odd even method [27], and a novel magic square technique [28] are developed to reduce the power losses during partial shading. However, these methods are not valid for all m × n PV arrays.

The aforementioned methods are either applicable to a particular m × n structure or need complex logical thinking like solving puzzles. For the cases where P-V characteristics exhibits more than one peak, a special algorithm is required to track global maximum power point. Thus, electrical characteristics with a single peak is always desirable for the PV arrays. Also, lesser the number of peaks lesser the complexity in tracking the global peak. The objective of the proposed method is to develop a simple algorithm based reconfiguration technique, applicable to any m × n structure and having electrical characteristics with reduced number of peaks. The proposed method is labelled as Algorithm based Total Cross Tied (ATCT) Configuration. The main contributions of this work are:

1) The algorithm gives a general method applicable to any m × n structure of PV arrays
2) Number of peaks in the P-V characteristics are either one or at most two only
3) A condition to achieve a single peak in P-V characteristics is discussed.

By MATLAB/SIMULINK simulations, performance of the proposed method is compared with existing topologies such as conventional TCT, Odd-Even TCT, Optimal TCT (OTCT) and Novel TCT (NTCT) using the performance analysis indices like P-V characteristics maximum power generated, number of peaks, partial shading losses and performance ratio and is illustrated that the proposed method gives superior performance over the other methods.

The remainder of this paper is organised as follows: Section II discusses the modeling of PV configuration and the discussion on the problems related to partial shading is presented in Section III. The proposed methodology is narrated with an example in Section IV. Section V presents analysis and comparison on the performance of the proposed algorithm with existing methods.

II. MODELING OF SOLAR PV PANEL WITH BYPASS DIODE

The strategy based on single diode model presented in [29]–[31] is one of the most acceptable modeling methods for a PV panel. A shaded solar cell can be considered as equal to a resistor which consumes energy created by neighboring cells. The absorbed energy produces heat and this phenomena is known as hot spot. This issue is resolved by using bypass diodes [4], [32], [33]. A model of a PV panel with bypass diode is shown in Figure 1. Here, $R_s$ and $R_{sh}$ are the series and shunt resistances, $I_{ph}$ and $I_s$ are photo current and generated PV panel current, $V_g$ is the output voltage of PV panel and $N_s$ is number of PV cells connected in series to constitute a PV panel.

The generated current for a panel with a bypass diode can be obtained as

$$I_g = \left[ I_{ph} - I_0 \left( e^{\frac{qV_g + R_s I_{ph}}{AKT}} - 1 \right) - \frac{V_g + R_s I_{ph}}{R_{sh} N_s} \right] + \left[ I_{obypass} \left( e^{\frac{-qV_g}{A_{obypass} KT}} - 1 \right) \right]$$

where, $I_0$ is reverse saturation current, $q$ is the electron charge, $A$ is a dimensionless material quantity, $T$ is the temperature in Kelvin, $I_{obypass}$ is the reverse saturation current of bypass diode [34], [35]. The specifications of PV module considered for simulation studies are shown in Table 1.

III. PROBLEM FORMULATION

Consider a PV array arranged in TCT configuration with r rows and c columns as shown in Figure 2. Here, all the modules in a row are connected in parallel and so voltage
Let $V_i$ be the voltage across any module and is assumed that it is same for all modules, $V_i = V_g$. Then voltage across the PV array can be obtained as,

$$V_{array} = \sum_{i=1}^{r} V_i = rV_g$$  \hspace{1cm} (2)

By Kirchhoff’s current law, the current delivered by $i^{th}$ row can be expressed as

$$I_i = \sum_{j=1}^{c} I_{ij} = cI_g$$  \hspace{1cm} (3)

across a row is same as voltage generated by a module ($V_g$).

Let $V_i$ be the voltage across any module and is assumed that it is same for all modules, $V_i = V_g$. Then voltage across the PV array can be obtained as,

$$P_{array} = r \sum_{i=1}^{r} V_i I_i = NV_g I_g$$  \hspace{1cm} (4)

where $N$ be the total number of PV modules in the PV array.

Let $q_i$ be the number of modules in the $i^{th}$ row which are partially shaded with a shading factor $S_f$, defined by

$$S_f = \frac{G}{G_{STC}}$$  \hspace{1cm} (5)

where, $G$ is the normal solar insolation level and $G_{STC}$ is the solar insolation at the standard testing condition (1000 W/m$^2$). The current generated by the the $i^{th}$ row for the shaded condition is derived as

$$I_i = q_i S_f I_g + (c - q_i) I_g = c I_g - (1 - S_f) q_i I_g$$  \hspace{1cm} (6)

take the derivative of $I_i$ with respect to $S_f$,

$$\frac{dI_i}{dS_f} = q_i I_g > 0$$  \hspace{1cm} (7)

Equation (7) implies that the row current decreases as $S_f$ decreases and hence the generated power is reduced.

It is obvious from Equation (6) that rows with distinct number of shaded modules ($q_i$) will generate different row currents. However, all rows are connected in series and so the load current will be the minimum current among all the row currents. In this paper, the load current is assumed as the current generated corresponding to global maximum power point (GMPP) of the PV array. The variation of $I_i$ against $q_i$ can be understood from the derivative of $I_i$ with respect to $q_i$

$$\frac{dI_i}{dq_i} = -(1 - S_f) I_g < 0$$  \hspace{1cm} (8)

which implies that row current decreases as $q_i$ increases. Hence, a row with maximum $q_i$ gives minimum row current. This current corresponds to load current which can be obtained by substituting $q_i = q_m$ in Equation (6)

$$I_L = c I_g - (1 - S_f) q_m I_g$$  \hspace{1cm} (9)

where

$$q_m = \max_{i=1}^{r}(q_i)$$  \hspace{1cm} (10)

Equation (9) gives the main idea of this paper which is stated as, “the load current and hence the generated power can be increased by minimizing $q_m$”.

The objective of this paper is to develop an algorithm to reduce $q_m$ which will lead to an improvement in the performance of PV modules under partial shading conditions. It is required to achieve an enhancement in the maximum generated power, reduction in the number of peaks in P-V characteristics and should possess higher performance ratio. Also, the algorithm should be applicable to any $m \times n$ structure of PV array.
IV. PROPOSED METHODOLOGY

As discussed in the Section III, the generated power can be improved by minimizing $q_m$. Let $r_m$ be the row for which number of shaded modules is maximum. One shaded module of this row is transferred to a row $r_i$ for which $q_i < q_m$ resulting in a decrease of $q_m$ by 1. The process is repeated until $max(q_i - min(q_i) = 0$ or 1 where,

$$\begin{align*}
\max q_i &= \max(q_1, q_2, q_3, \ldots, q_r) \\
\min q_i &= \min(q_1, q_2, q_3, \ldots, q_r)
\end{align*}$$

The proposed algorithm is explained using an example.

Consider a 6×4 PV array with assumed shading pattern as shown in Figure 3(A). It is assumed that all the shaded panels receive the insolation level of 500 W/m² and unshaded panels receive 1000 W/m².

1) Construct a matrix $A$ as follows

$$A = \begin{bmatrix}
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 \\
1 & 1 & 1 & 0 \\
1 & 1 & 1 & 1
\end{bmatrix}$$

2) Find the ‘row sum’

$$S_R(i) = \sum_{j=1}^{c} A_{ij}, \quad i = 1, \ldots, r$$

3) Prepare a table, known as ‘row sum table’ with fields ‘row number’ (i) and corresponding ‘row sum $S_R(i)$’.

| Row number (i) | Row sum $S_R(i)$ |
|---------------|------------------|
| 1             | 1                |
| 2             | 1                |
| 3             | 1                |
| 4             | 2                |
| 5             | 3                |
| 6             | 4                |

4) Get the first column number $j$ of the $l^{th}$ row with $A_{lj} = 0, j = 1, 2, 3, \ldots, c$ and designate the column number as $u$. The cell $A_{lu}$ is the first unshaded module of $l^{th}$ row.

Here $u = 2$

5) Get the first column number $j$ of the $h^{th}$ row with $A_{hj} = 1, j = 1, 2, 3, \ldots, c$ and designate the column number as $s$. The cell $A_{hs}$ is the first shaded module of $h^{th}$ row. Here $s = 1$

6) Interchange cells $A_{lu}$ and $A_{hs}$

For the case considered, interchange $A_{12}$ and $A_{61}$

7) After the interchange, the matrix is changed to

$$A = \begin{bmatrix}
1 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 \\
1 & 1 & 1 & 0 \\
0 & 1 & 1 & 1
\end{bmatrix}$$

8) Continue steps 1 to 7 until

$$\max(S_R(i)) - \min(S_R(i)) = 0$$

9) Condition given by Equation (14) can be achieved only if

$$\sum_{r}(S_R(i))$$

is an integer. Otherwise continue the iterations until

$$\max(S_R(i)) - \min(S_R(i)) = 1$$

The modules being interchanged at each iteration are presented in Table 3 and the final matrix representation is

$$A = \begin{bmatrix}
1 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 \\
1 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 \\
0 & 0 & 1 & 1
\end{bmatrix}$$

The shading pattern after the interconnection of the modules as per the proposed algorithm is depicted in Figure 3(B).

The P-V characteristics of TCT and ATCT are shown in Figure 4. It is clear from the figure that characteristics of TCT configuration gives a maximum power of 482 W under unshaded conditions. However, during shaded condition, the P-V characteristics exhibit four peaks and the global maximum power is reduced to 274.4 W. Whereas, the proposed algorithm enhances the maximum power point to 356 W with a definite increase of 81.6 W. Also, the number of peak points is reduced to one. The proposed methodology is described in Algorithm 1

**Proposition 1:** The proposed algorithm makes sure that there are utmost two peaks in the power - voltage (P-V) characteristics of partially shaded PV arrays.
Algorithm 1: Proposed Methodology (ATCT)

1. initialization;
2. input : Number of rows(r) and number of columns(c)
3. Construct the matrix A as follows
4. if module $ij$ is unshaded then
   5. $A_{ij} = 0$
5. else
6. $A_{ij} = 1$
8. end
9. Find the ‘row sum’ $S_R(i) = \sum_{j=1}^{c} A_{ij}, i = 1, \ldots, r$
10. while ($\max S_R(i) - \min S_R(i) > 0 \& \sum S_R(i)\%c = 0$) or ($\max S_R(i) - \min S_R(i) > 1 \& \sum S_R(i)\%c \neq 0$)
   11. Prepare the 'row sum table (RT)';
12. for $i \leftarrow 1$ to $r$ do
13. $RT(i, 1) = i$
14. $RT(i, 2) = S_R(i)$
15. end
16. Arrange the ‘row sum table (RT)’ in ascending order of $S_R(i)$
17. Designate the first-row number of the table with the minimum $S_R(i)$ as $l$
18. Get the first column number $j$ of the $l^{th}$ row with $A_{lj} = 0, j = 1, 2, 3, \ldots c$ and designate the column number as $u$.
19. Get the first column number $j$ of the $h^{th}$ row with $A_{hj} = 1, j = 1, 2, 3, \ldots c$ and designate the column number as $s$.
20. Interchange cell elements $A_{lu}$ and $A_{hs}$
21. Find the ‘row sum’ $S_R(i) = \sum_{j=1}^{c} A_{ij}, i = 1, \ldots, r$
22. end

Proof: Let the row sum $S_R(i)$ is maximum for $i = p$ and minimum for $i = q$. If there are $n_1$ rows with row sum $S_R(p)$ and $n_2$ rows with row sum $S_R(q)$, then $p$ and $q$ can be any row number from these $n_1$ and $n_2$ rows, respectively. As per the proposed algorithm, one shaded module of row $p$ shall be transferred to row $q$. Thus, as the algorithm proceeds, max $S_R(i)$ cannot increase and min $S_R(i)$ cannot decrease than their current values. After $n_1$ iterations, $S_R(p)$ is reduced to $S_R(p) - 1$. Similarly after $n_2$ iterations, $S_R(q)$ is increased to $S_R(q) + 1$. The process continues and a stage will reach where max $S_R(i) - \min S_R(i) = 0$ or 1.

If max $S_R(i) - \min S_R(i) = 1$, then number of shaded modules of each row will be either max $S_R(i)$ or min $S_R(i)$ which implies that, there are only two row groups having same number of shaded modules and so only two peaks are present in the P-V characteristics.

On the other hand, if max $S_R(i) - \min S_R(i) = 0$, then all the rows have equal number of shaded modules resulting in a single row group having same number of shaded modules and thus, only one peak in the characteristics. □

Corollary 1: It can be deduced from Proposition 1 that the proposed algorithm provides only a single peak in P-V characteristics if

$$\sum S_R(i)\%c = 0$$
FIGURE 6. P-V Characteristics of the case studies shown in Figure 5.
Proof: Let \( r_{\text{max}} \) be the number of rows which have \( \max S_R(i) \) number of shaded modules and \( r_{\min} \) be the number of rows having \( \min S_R(i) \) number of shaded modules.

At the final stage of the algorithm, let \( r_{\text{max}} = z \). Then \( r_{\min} = r - z \). This leads to

\[
\sum S_R(i) \% r = 0 \quad (17)
\]

\[
\Rightarrow (z \max S_R(i) + (r - z) \min S_R(i)) \% r = 0 \quad (18)
\]

\[
\Rightarrow (z [\max S_R(i) - \min S_R(i)] + r \min S_R(i)) \% r = 0 \quad (19)
\]

\[
\Rightarrow (z [\max S_R(i) - \min S_R(i)]) \% r = 0 \quad (20)
\]

\[
\Rightarrow z \% r [\max S_R(i) - \min S_R(i)] = 0 \quad (21)
\]

\[
\Rightarrow z \% r = 0 \quad \text{and/or} \quad \max S_R(i) - \min S_R(i) = 0 \quad (22)
\]

The conditions \( z \% r = 0 \) and \( \max S_R(i) - \min S_R(i) = 0 \) can only be satisfied simultaneously. Either of these conditions implies that all rows have equal number of shaded modules, resulting in a single peak in P-V characteristics.

\[\square\]

V. RESULTS AND DISCUSSIONS

This section compares the performance of the proposed algorithm with existing methods like conventional TCT, odd even TCT, Optimal TCT and Novel TCT. The comparison is done for \( 4 \times 4 \times 3 \) and \( 3 \times 4 \) configurations. This section also validates the proposition 1 on the number of maximum peak points in P-V characteristics.

PARAMETERS FOR PERFORMANCE ANALYSIS

Performance parameters such as maximum generated power, P-V characteristics, power loss, performance ratio and number of peak points are considered for performance analysis and comparisons. The maximum generated power and number of peak points can be obtained from P-V characteristics. The power loss is defined as the difference between the generated power during unshaded condition at standard testing condition to maximum power generated during partial shading case. The performance ratio is the ratio of maximum power generated during partially shaded conditions to the power generated during standard testing condition.

A. ANALYSIS AND COMPARISON OF \( m \times n \) PV ARRAY WITH \( m=n \)

The performance of proposed ATCT is compared and analysed with conventional and odd even TCT configurations. The analysis is done on the basis of maximum generated power, power loss, performance ratio and number of peaks in P-V characteristics. The details on arrangement of PV modules by odd even TCT can be obtained from [19]. For the analysis and study, eight cases with shading patterns as shown in Figure 5 are considered. It is assumed that all the shaded panels receive only 20% of standard insolation value and unshaded panels receive 1000 W/m\(^2\).
1) P-V CHARACTERISTICS
The PV characteristics of $4 \times 4$ PV array for various case studies are depicted in Figure 6. The maximum generated power and the number of peaks for each case can be obtained from the P-V characteristics. Figure 7(A) analyses the maximum generated power for the three methods, and it is evident that the proposed ATCT method gives more generated power for all the cases. The improvements in generated power are 16.7 W, 6.2 W, 42.6 W, 38.8 W, 34.8 W, 5.4 W, 4.2 W, and 30.36 W for the Cases 1 to 8, respectively.

![Figure 9. P-V Characteristics of case studies.](image)

![Figure 10. Performance analysis.](image)
Here, the improvement is calculated as the difference between power generated by ATCT and the maximum power output of the other two methods.

2) NUMBER OF MAXIMUM POWER POINTS

Table 4 presents the number of peaks in P-V characteristics. If the characteristics exhibits only one peak point, then conventional algorithms are sufficient to track the maximum power. However, if it exhibit multiple peaks, then special algorithm is required to track the global peak point. Table 4 illustrates that number of peak points are reduced to 1 for the cases 1, 3 & 5. For the case considered, the proposed method gives at-most two maximum peaks in P-V characteristics. However, this value is 4 for TCT and 3 for odd even. Thus it can be concluded from this Table (as illustrated by proposition 1) that maximum number of peaks for the proposed algorithm is only 2 and is reduced to single peak point for the cases where $\sum S_f(i) \bmod r = 0$.

3) PARTIAL SHADING LOSSES

The performance of a particular method can be ascertained from partial shading losses. Lesser the losses, better the performance. It is evident from Figure 7(B) that the partial shading losses for the proposed method are minimum for all the eight cases. The partial shading losses of proposed method are reduced by 16.7 W, 6.2 W, 42.6 W, 38.8 W, 34.8 W, 5.4 W, 4.2 W, and 30.36 W for the Cases 1 to 8, respectively. Here, the reduction in losses is calculated as the difference between minimum losses among the two methods and partial shading losses of ATCT.

4) PERFORMANCE RATIO (PR)

Performance ratios of different configurations are shown in Figure 7(C). It is clear from the figure that proposed ATCT method gives higher performance ratio against the other two methods. Improvements in the performance ratio are 5.20%, 1.93%, 13.27%, 10.84%, 1.68%, 1.31%, and 9.46% for the Cases 1 to 8, respectively. Here, the improvement in performance is calculated as the difference between performance by ATCT and the maximum performance among the other two methods.

B. ANALYSIS AND COMPARISON OF $m \times n$ PV ARRAY WITH $m > n$

This section illustrates the fact that the proposed method is applicable to the case with unequal number of rows and columns also. Hence, a PV array with $4 \times 3$ dimension is considered and the performance is compared with OTCT (Optimal TCT), NTCT (Novel TCT) [14], and TCT. Six case studies with shading patterns as shown in Figure 8 is considered for the analysis. For this study, the shading factor $S_f$ is assumed as 0.3.
fact that maximum number of peaks in P-V characteristics is 2. Figures 10(B) and 10(C) illustrate that proposed method gives an optimum partial shading loss and performance ratio as compared to other methods.
Figure 10(A) illustrates that the proposed method achieves an improvement of 27.7 W, 26.5 W, 27.7 W, 34.5 W, and 34.5 W in the generated powers for the cases 2 to 6 and maintains the maximum generated power among other three methods. For the proposed method, the partial shading losses are reduced by 0 W, 27.7 W, 26.5 W, 27.7 W, 34.5 W and 34.5 W and performance ratio are improved by 0%, 11.49%, 11.00%, 11.49%, and 14.32% for the Cases 1 to 6, respectively.

C. ANALYSIS AND COMPARISON OF $m \times n$ PV ARRAY WITH $m<n$

A $3 \times 4$ PV array is considered to analyse and illustrate the case where, the number of rows is less than the number of columns. The case studies with six different shading patterns as shown in Figure 11 with a shading factor 0.5 is considered for the analysis. The maximum power generated and number of peak points can be observed from the PV characteristics shown in Figure 12. Figure 13(A) illustrates that the proposed
method achieves an improvement of 19.3 W, 4.8 W, 33.8 W, 50 W, 17.2 W and 16 W in the generated power for the cases 1 to 6 and maintains the maximum generated power as compared to TCT configurations. For the proposed method, the partial shading losses are reduced by 19.3 W, 4.8 W, 33.8 W, 50 W, 17.2 W and 16 W, whereas, performance ratio are improved by 8.01%, 1.99%, 14.02%, 20.75%, 7.14% and 6.64% for the cases 1 to 6, respectively and these results are depicted in the Figures 13(B) and 13(C). Table 6 shows the number of peak points for different case studies. For cases 5, 6 the number of peak points is reduced from 3 to 1.

D. VALIDATION OF PROPOSITION ON NUMBER OF MAXIMUM POWER POINTS

Figure 14 shows the shading patterns considered to analyze the proposition on number of peaks. The number of peaks for ATCT and TCT configurations for a 6 × 6 PV array with shading factor $S_{f} = 0.5$ are shown in Figure 15. The terms $n_{TCT}$ and $n_{ATCT}$ in the remarks column of Table 7 indicate the number of maximum power points for TCT and ATCT configurations, respectively. It is clear from Figure 15 that the proposed method provides at-most two peaks in P-V characteristics. This result is in tune with proposition 1. The proposed ATCT gives a single peak for the cases 1, 3, 5, & 6, where $\sum S_{R}(i)\%r = 0$ and the number of peaks for ATCT is 2 for the remaining cases for which $\sum S_{R}(i)\%r \neq 0$.

VI. CONCLUSION

This paper presented an algorithm to achieve enhanced performance of PV modules under partial shading conditions. The main challenges due to partial shading are (i) reduction in generated power and (ii) increase in the number of peaks in power-voltage (P-V) characteristics. It has been established in this paper that dispersing shaded modules to various rows, such that all rows receive equal or nearly equal number of shaded modules, can result in improved generated power and reduced number of maximum power points. An algorithm is presented in this paper to disperse shaded modules such that difference between maximum and minimum among the number of shaded modules of all rows is either zero (all rows gets equal number of shaded modules) or one. A proposition is presented which states that the P-V characteristics exhibits only one peak if total number of shaded modules divided by number rows is an integer. It is also proved that adoption of the proposed algorithm gives a P-V characteristics with at-most two peaks. Comparative simulation studies was carried out on 4 × 4, 4 × 3, and 3 × 4 PV arrays, to show that the proposed method is applicable to any m × n PV array. The simulation studies has proved that the proposed method is capable of generating improved power as compared to the existing methods (TCT, odd even TCT, OTCT, and NTCT). To validate the proposition on number of peaks six different shading cases on 6 × 6 PV array is considered and the proposed ATCT gives a single peak for the cases 1, 3, 5, & 6. The enhancement in generated power for six different shading pattern are 9.42%, 9.70%, 21.10%,7.76%, 6.45%, and 24.12%. As a future work, a global maximum power point tracking algorithm can be developed and combined with proposed method to extract the enhanced generated power.

### TABLE 7. Remarks on validation of proposition.

| Cases | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
|-------|--------|--------|--------|--------|--------|--------|
| Remarks | $\sum S_{R}(i)\%r = 0$ | $n_{TCT} = 2$ | $n_{ATCT} = 1$ | $\sum S_{R}(i)\%r = 5$ | $n_{TCT} = 2$ | $n_{ATCT} = 1$ |
| | | | | $\sum S_{R}(i)\%r = 0$ | $n_{TCT} = 2$ | $n_{ATCT} = 1$ |
| | | | | $\sum S_{R}(i)\%r = 4$ | $n_{TCT} = 2$ | $n_{ATCT} = 1$ |
| | | | | | | $\sum S_{R}(i)\%r = 0$ | $n_{TCT} = 5$ | $n_{ATCT} = 1$ |

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