An MMTES algorithm for dynamic photovoltaic array reconfiguration to enhance power output under partial shading conditions

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Abstract
Partial shading is a severe impediment to the effective use of photovoltaic systems. It will lead to performance degradation in the photovoltaic system. This work proposes a maximum–minimum tier equalisation swapping reconfiguration algorithm for total-cross-tied connection under shading conditions. The proposed reconfiguration algorithm uses a switch matrix to alter the interconnection of modules in a photovoltaic array. The switch matrix dynamically modifies the connections based on the equalisation of tier irradiance. This algorithm applies to the symmetrical and asymmetrical photovoltaic array. Further, simulation studies show the efficacy of the proposed algorithm by minimising the multiple peaks and enhancing the output power compared with the traditional total-cross-tied configuration. The performance of experimental tests ascertains the feasibility of the proposed method.

1 | INTRODUCTION

The constraints on conventional energy sources prioritise the use of renewable for power generation. Among them, solar energy is majorly used because of its diverse applications and numerous advantages. Generally, the power developed by a single photovoltaic (PV) module is insufficient to meet the desired load requirement. So, several modules are tied in series or parallel or in other configurations to create an array. Partial shading is the major problem in PV arrays [1]. It occurs due to non-homogeneous irradiances at various modules in an array, as discussed in [2]. Such modules, connected in series, leads to undesirable effects like hot spots, mismatch power losses and reduction of power output.

Many methods are proposed to improve PV system performance under Partial Shading Conditions (PSC) [3]. The primary solution is connecting a bypass diode in parallel with each PV module. This approach prevents the PV module from hot spot effect [4], but it requires a high number of bypass diodes. Besides, they exhibit multiple peaks in the $P - V$ and $I - V$ curves, which in turn requires complex algorithms to track the global peak [5, 6]. Many optimisation algorithms are used to track maximum global power [7–10]. These optimisation algorithms are sometimes unable to guarantee the detection of the global peak. Further, the ability to find the global peak depends on the selection, population size, initialisation of the parameters and the formulation of the objective function, which involves high computational burden.

The secondary solution is using several PV array configurations. These configurations depend on various electrical interconnections between the modules. Among several configurations, TCT is the most appealing interconnection scheme which delivers maximum power under shading conditions [11]. However, in some cases, the Honeycomb (HC) configuration offers greater power compared with the other configurations due to fewer ties [12]. So, there is not a single interconnection scheme which provides better performance for all the shading conditions. Power electronic converters with maximum power point tracking (MPPT) algorithm to each PV module mitigates the partial shading effect [13]. Although this solution assures that each PV module extracts the maximum available energy, it requires a large number of converters.

Reconfiguration has emerged as an alternative and innovative solution to improve power output under shading conditions.
Reconfiguration techniques are broadly classified as static and dynamic. In static reconfiguration, the position of modules changes without amending the electrical connections. The rearrangement of modules depends on various puzzle patterns for shade dispersion like Futoshiki, PRM-FEC, and Sudoku [14–17]. Neither sensors nor switch network requires for these techniques. Nevertheless, to configure the position of PV modules, it needs an adequate reconfigurable pattern to scatter the shade across the array. Further, it requires skilled labour and complicated rewiring.

In spite, with the advent of high rating semiconductor switches, data acquisition sensors and advanced processors make dynamic photovoltaic array reconfiguration (DPVAR) an eminent solution to mitigate the effect of partial shading conditions. In DPVAR, the panel’s physical locations remain the same. However, the electrical connections change according to the shading condition [19–29]. Various DPVAR techniques have been proposed by the researchers across the globe. A mathematical formulation based on mixed-integer quadratic programming is proposed in [19], where the optimal solution is determined using branch and bound global optimisation algorithm. These global optimisation algorithms are complex for implementation. The work presented in [20] applies irradiance equalisation approach on module integrated (MI), module-oriented (MO) and plant-oriented (PO) configurations. It proved that the PO yields better results under irradiance equalisation approach. A particle swarm optimisation (PSO) is applied for DPVAR in [21]. However, it has complexity in the formulation of the objective function and parameter tuning. The algorithm proposed in [22] aims for the reduction of the switch count. The algorithm is, however, restrained to repeated shading conditions. Nguyen et al. [23] has proposed an adaptive reconfiguration model to mitigate partial shading effect. In this model, the most illuminated cell in an adaptive bank is connected to the shaded row in the fixed part via a switch matrix. However, the number of modules required for this model is more to enhance the power output. Further, the algorithm computes the difference between maximum irradiance and minimum irradiance using all the combinations of irradiances which requires more processing time to find the best configuration. The algorithm used in [20, 27] are based on irradiance equalisation for TCT connection, but the number of combinations required to verify the best configuration is more. A sorting-based reconfiguration algorithm is implemented on TCT connected PV array for enhancement of power in PV array [24]. However, it requires extra adaptive PV panels to enhance the output power. An electrical array reconfiguration scheme is proposed [25] for 3 × 3 PV array. It optimises the configurations which deliver the maximum output power. The algorithm uses triple pole single throw switches which minimises the switch count. However, the switches required for the algorithm are asymmetrical. Similarly, asymmetrical PV modules are required in an array for the algorithm proposed in [26]. This asymmetrical nature increases the complexity of the algorithm. An improved optimisation [27] for DPVAR reconfiguration is proposed for tier equalisation in an array. However, it has constraints on the number of rows in a PV array. A comparison of various PV array architectures and algorithms are made in [28]. The algorithm proposed in [29] uses a double pole double throw (DPDT) switches for reconfiguration. Although it uses less number of switches, the algorithm is complex. Based on the above discussion, with the advancement in technology DPVAR provides a feasible solution for power enhancement under shading conditions. To overcome the shortfalls in the existing literature [19–29] for DPVAR, this paper proposes a maximum-minimum tier equalization swapping (MMTES) algorithm. The proposed method falls under the sorting type reconfiguration algorithm (SRA) and PO configuration. The algorithm alters the position of modules with the help of a switch matrix.

The main contributions of the paper are summarised as follows.

i. This work proposes a simple algorithm to make the tier irradiiances equal (irradiance equalisation).

ii. The proposed MMTES algorithm applies to any size PV-array (symmetrical and asymmetrical).

iii. The proposed algorithm equalises the irradiance at any complex shading conditions.

iv. The algorithm uses the minimum number of configurations to find the optimal configuration which delivers maximum power.

The remainder of the paper is structured as follows: Section 2 deals with the summary of the system, Section 3 elucidates the MMTES algorithm, Section 4 analyses the simulation results, Section 5 gives the details of the experimental verification, and finally, Section 6 ends with a conclusion.

## 2 | SYSTEM DESCRIPTION

### 2.1 | TCT configuration

Among several configurations, the TCT configuration is considered for reconfiguration as it delivers maximum power for most of the shading patterns [11]. Figure 1 represents the TCT configuration of 3 × 3 PV array. In TCT connection, each row is cross-linked in a simple series and parallel fashion. The current produced by the module at the specific irradiance $G$ is given by

$$I_{ij}(\text{shaded}) = KL_{ij}(\text{standard}),$$

where $K = \frac{G_{ij}}{G_{STC}}$, \hspace{1cm} (2)

where $i$ and $j$ represent the row and column of an array. $I_{ij}(\text{shaded})$ and $I_{ij}(\text{standard})$ represent the module current, during shaded and standard irradiance (1000 w/m²) conditions. $G_{ij}$ represents the irradiance received by the $ij$ module and $G_{STC}$ represents standard irradiance. The PV array voltage is as follows:

$$V_a = \sum_{i=1}^{n} V_r,$$
where \( m \) indicates the total number of tiers, \( i \) indicates the tier number, \( V_i \) is the voltage of the \( i \)th tier and \( V_a \) represents the array voltage.

### 2.2 Switches and sensor requirement

Switch network is a significant component in DPVAR. Figure 2 shows the switch network of the PV module using a single pole single throw switches. The number of switches and sensors required for reconfiguration depends on the number of modules and tiers. For an \( m \times n \) pv array, the total number of switches \( (S_T) \) is given by the equation:

\[
S_T = S_P \times S,
\]

where \( S_P = 2 \times m \),

\[
S = m \times n.
\]

Here \( S_P \) represents the number of switches for a PV module and \( S \) represents number of irradiance sensors. For a \( 3 \times 3 \) PV array, when the switch \( S_1 \) and \( S_4 \) are ‘ON’, then the module is located in tier-1. When the switches \( S_2 \) and \( S_5 \) are triggered, then the module is in tier-2. Similarly, by triggering \( S_3 \) and \( S_6 \), the module relocates to tier-3. During reconfiguration, the module moves to corresponding tiers based on the algorithm. The switching is simple and straightforward to implement.

### 3 | PROPOSED MMTES ALGORITHM

Figure 3 shows the block diagram of the proposed DPVAR. The irradiance is proportional to the PV current. To improve the output power, the algorithm aims to maintain equal current in all the tiers. The switch matrix alters the connection of modules in the array to make tier irradiance equal. The MMTES algorithm broadly has four stages: Initialisation, sorting, identification of minimum and maximum tiers and exchanging the elements from the maximum tier to a minimum tier. Figure 4 shows the flowchart of the proposed MMTES algorithm. The MMTES algorithm ensures the optimum configuration of the switches that equalise the irradiance in each tier (row) of the PV array [25]. The following steps briefly describe the working of the proposed algorithm.

#### Step-1:

It mainly focuses on initialisation and acquisition of data. The algorithm needs data of irradiance of each module within the array. The algorithm collects the irradiance of each module from the corresponding irradiance sensor. Let \( G \) and \( P \) indicate the irradiances and its corresponding position of modules, respectively, in a PV array \((m \times n)\). \( Z \) indicates the summation of rows
The main objective of the algorithm is to maintain all the elements of \( Z \) matrix near to the set value. The algorithm computes the set value based on the irradiances as given below:

\[
\text{Set value} = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} G_{ij}}{m}.
\]  

(7)

Step-3:

The algorithm sorts the elements of \( G, P \) matrix, in column-wise increasing order. The \( Z \) matrix is calculated from the corresponding sorted \( G \) matrix. The algorithm terminates if each element in \( Z \) is equal to the set value. If any element in \( Z \) is not equal to set, then the algorithm proceeds to step-4. In the flowchart, \( i \) indicates the row index of elements in \( Z \) matrix.

Step-4:

If all the elements in \( Z \) are not equal to the set value (as per Equation (7)), then the algorithm determines the smallest element index \( \text{Min}_\text{row}_k \) and largest element index \( \text{Max}_\text{row}_k \) in \( Z \). Here, \( k \) indicates the iteration number.

Step-5:

Let \( u \) and \( v \) indicates the position of irradiances in rows of \( G \) matrix corresponding to \( \text{Max}_\text{row}_k \) and \( \text{Min}_\text{row}_k \). Some of the irradiances in these two rows of the \( G \) matrix need to be swapped to make all the values of \( Z \) matrix near to set value. For an \( m \times n \) size PV array, \( n^2 \) comparisons are possible between each element in \( \text{Max}_\text{row}_k \) and \( \text{Min}_\text{row}_k \). Among \( n^2 \) comparisons, only the element in \( \text{Max}_\text{row}_k \) of \( G \), which is greater than the element in \( \text{Min}_\text{row}_k \) of \( G \) are necessary for possible swapping.

Step-6:

The algorithm compares the elements in \( G \) matrix corresponding to \( \text{Max}_\text{row}_k \) and \( \text{Min}_\text{row}_k \) and selects a pair of elements for swapping. The algorithm determines the pair of elements, by finding the difference between each pair of elements, and compares with the difference between the maximum value of \( Z \) and set value based on Equation (8).

\[
D(u, v) = \text{abs}[G(\text{Max}_\text{row}_k, u) - G(\text{Min}_\text{row}_k, v)] - (\text{max}(Z) - \text{set value})
\]

\( \forall \ 1 \leq u \leq m, 1 \leq v \leq n. \)  

(8)

The pair of elements corresponding to \( \text{min}(D(u, v)) \) represents the best selection for swapping. The positions of this selected elements are stored in \( p_k \) and \( q_k \).

Step-7:

In the initial iteration, the algorithm swaps the \( p_k \) and \( q_k \) elements corresponding to the \( \text{Max}_\text{row}_k \) and \( \text{Min}_\text{row}_k \) row, and the corresponding positions are also swapped in position matrix. The iterations will continue until all the values in \( Z \) matrix are equal to set value or the elements swapped in the previous iteration are being swapped in the present iteration. If the two consecutive iterations choose same elements for swapping, then the loop will be terminated.

The working principle of the MMTES algorithm is explained with an example. Table 1 shows the step-by-step approach to
TABLE 1 Illustration of the proposed algorithm for case- I

| Step | G = | P = | Z = |
|------|-----|-----|-----|
| 1    | \[
\begin{bmatrix}
400 & 500 & 600 \\
500 & 600 & 700 \\
600 & 700 & 800
\end{bmatrix}
\] | \[
\begin{bmatrix}
P_{11} & P_{12} & P_{13} \\
P_{21} & P_{22} & P_{23} \\
P_{31} & P_{32} & P_{33}
\end{bmatrix}
\] | \[
\begin{bmatrix}
1500 \\
1800 \\
2100
\end{bmatrix}
\] |

Step:2
Set value = \(5400/3 = 1800\)

Step:3
\[
G = \begin{bmatrix}
400 & 600 & 700 \\
500 & 600 & 700 \\
600 & 600 & 800
\end{bmatrix}, \quad P = \begin{bmatrix}
P_{11} & P_{12} & P_{13} \\
P_{21} & P_{22} & P_{23} \\
P_{31} & P_{32} & P_{33}
\end{bmatrix}, \quad Z = \begin{bmatrix}
1700 \\
1800 \\
1900
\end{bmatrix}
\]

Step:4
Min \(_{raw_1}=1\)
Max \(_{raw_1}=3\)

Step:5
\(a_1 = 500; a_2 = 600; a_3 = 800\)
\(r_1 = 400; r_2 = 600; r_3 = 700\)
possible nine combinations are
\((a_1, r_1), (a_1, r_2), (a_1, r_3), (a_2, r_1), (a_2, r_2), (a_2, r_3), (a_3, r_1), (a_3, r_2), (a_3, r_3)\)
out of which five combinations where \(a > r\) are considered
\((a_1, r_1), (a_2, r_1), (a_3, r_1), (a_3, r_2), (a_3, r_3)\)

Step:6
\(D(1, 1) = abs((500-400)-(1900-1800)) = 0;\)
\(D(2, 1) = 100; D(3, 1) = 300; D(3, 2) = 100; D(3, 3) = 0\)
\(p_1=1; q_1=1\)
Step:7
Swap \(G(3, 1) \& G(1, 1)\)
Swap \(P(3, 1) \& P(1, 1)\)
\[
G = \begin{bmatrix}
500 & 600 & 700 \\
500 & 600 & 700 \\
400 & 600 & 800
\end{bmatrix}, \quad P = \begin{bmatrix}
P_{12} & P_{11} & P_{13} \\
P_{21} & P_{22} & P_{23} \\
P_{31} & P_{32} & P_{33}
\end{bmatrix}, \quad Z = \begin{bmatrix}
1800 \\
1800 \\
1800
\end{bmatrix}
\]

achieve irradiance equalisation. The efficacy of the proposed algorithm is analysed in the following section by considering four different cases.

4 SIMULATION RESULTS AND ANALYSIS

The PV module specifications are given in Table 2. Simulation studies are performed and analysed for different cases.

Case-I:
In this case, a static oblique shading pattern is considered as shown in Figure 5. This shading ensures multiple peaks in the \(P-V\) curves. The corresponding tier currents for TCT connection is given by
\[
I_{R1} = \left( \left( \frac{600}{1000} \right) + \left( \frac{700}{1000} \right) + \left( \frac{800}{1000} \right) \right) \times I_\varphi = 2.1 \times I_\varphi.
\] (9)
\[
I_{R2} = \left( \left( \frac{500}{1000} \right) + \left( \frac{600}{1000} \right) + \left( \frac{700}{1000} \right) \right) \times I_\varphi = 1.8 \times I_\varphi.
\] (10)

As the current in three tiers is different from each other, multiple peaks occur in \(P-V\) curve, as shown in Figure 6. After reconfiguration, the modules 1 and 8 swaps their positions to make the irradiance equal. The current in each tier after reconfiguration is given by
\[
I_{R1} = \left( \left( \frac{500}{1000} \right) + \left( \frac{600}{1000} \right) + \left( \frac{700}{1000} \right) \right) \times I_\varphi = 1.8 \times I_\varphi.
\] (12)
\[
I_{R2} = \left( \left( \frac{500}{1000} \right) + \left( \frac{600}{1000} \right) + \left( \frac{700}{1000} \right) \right) \times I_\varphi = 1.8 \times I_\varphi.
\] (13)
\[
I_{R3} = \left( \left( \frac{400}{1000} \right) + \left( \frac{600}{1000} \right) + \left( \frac{800}{1000} \right) \right) \times I_\varphi = 2.1 \times I_\varphi.
\] (14)

Since after reconfiguration, all the tier irradiance becomes equal. The corresponding tier currents will be the same. So it is evident from Figure 6, a single global peak occurs. The
TABLE 2  Solar panel specifications for simulation

| Parameters | Values |
|------------|--------|
| $V_{oc}$   | 36.3 V |
| $I_{sc}$   | 7.84 A |
| $V_{mp}$  | 29 V   |
| $I_{mp}$  | 7.35 A |
| Area      | 1.57 m² |

TABLE 3  Comparison of currents, voltages and powers of TCT and MMTES based TCT for different cases from $P - V$ and $I - V$ curves

| Cases | Configuration | Gmpp (W) | Vmpp (V) | Imp (A) | Voc (V) | Isc (A) |
|-------|---------------|----------|----------|---------|---------|---------|
| I     | TCT           | 1119.6   | 94.07    | 11.9    | 108.9   | 17.19   |
|       | MMTES         | 1233     | 90.22    | 13.66   | 108.1   | 14.82   |
| II    | TCT           | 1060.5   | 95.75    | 11.07   | 108.9   | 17.19   |
|       | MMTES         | 1223     | 91.53    | 13.36   | 108.2   | 15.54   |
| III   | TCT           | 1781     | 93.95    | 18.97   | 109.6   | 26.16   |
|       | MMTES         | 1916     | 89.76    | 21.34   | 108.8   | 22.94   |
| IV    | TCT           | 877.2    | 62.07    | 14.13   | 108.2   | 22.08   |
|       | MMTES         | 1188     | 89.89    | 13.21   | 107.7   | 14.71   |

corresponding voltage, current and power are presented in Table 3. Based on these values mismatch losses, fill factor, performance ratio and efficiency are determined which are listed in Table 4. The global peak power of the array when all the modules are subjected to 1000 W/m² is 2058.6 W. The output power has been enhanced by 10.12% where the mismatch losses are reduced by 13.7% compared to the conventional TCT configuration. The simulation results show the effectiveness of the proposed algorithm by eliminating the multiple peaks and enhancing the output power.

Case-II:
Consider a PV array with random shading pattern as shown in Figure 7. This case demonstrates the effectiveness of the proposed algorithm by minimising the number of peaks in $P - V$ curve. The tier currents before reconfiguration for Case-II are represented as follows:

$$I_{R1} = \left( \frac{700}{1000} \right) + \left( \frac{700}{1000} \right) + \left( \frac{700}{1000} \right) \times I_m = 2.1 \times I_m,$$

$$I_{R2} = \left( \frac{700}{1000} \right) + \left( \frac{600}{1000} \right) + \left( \frac{600}{1000} \right) \times I_m = 2.0 \times I_m,$$

$$I_{R3} = \left( \frac{600}{1000} \right) + \left( \frac{500}{1000} \right) + \left( \frac{300}{1000} \right) \times I_m = 1.4 \times I_m.$$  

Before reconfiguration the difference in current between the tier-1 (row-1) and tier-2 is small as represented in Equations (15) and (16). Therefore, an anomaly occurs in the $P - V$ curve as shown in Figure 8. Since, three-tier irradiances are different, three different peaks occur. After reconfiguration, tier-1 and tier-2 have same currents, and tier-3 has different current as indicated in Equations (18)–(21). As a result, two peaks occur in the $P - V$ curve, as shown in Figure 8. The output power is increased by 15.32% compared to the conventional TCT configuration.

$$I_{R1} = \left( \frac{600}{1000} \right) + \left( \frac{600}{1000} \right) + \left( \frac{700}{1000} \right) \times I_m = 1.9 \times I_m,$$

$$I_{R2} = \left( \frac{500}{1000} \right) + \left( \frac{700}{1000} \right) + \left( \frac{700}{1000} \right) \times I_m = 1.9 \times I_m,$$

$$I_{R3} = \left( \frac{300}{1000} \right) + \left( \frac{700}{1000} \right) + \left( \frac{700}{1000} \right) \times I_m = 1.7 \times I_m.$$  

The mismatch losses are reduced nearly by 16.27%. The fill factor, performance ratio and efficiency increase compared to the conventional TCT configuration.

Case-III:
This case demonstrates that the algorithm works for asymmetrical ($m \neq i$) PV array. The shading is such a way that the first pair of modules and the last pair of modules in each tier receive the same irradiances. The tier currents of the array for fixed TCT is represented as follows:

$$I_{R1} = 2 \times \left( \frac{700}{1000} \right) + 2 \times \left( \frac{900}{1000} \right) \times I_m = 3.2 \times I_m,$$

$$I_{R2} = 2 \times \left( \frac{600}{1000} \right) + 2 \times \left( \frac{800}{1000} \right) \times I_m = 2.8 \times I_m,$$

$$I_{R3} = 2 \times \left( \frac{500}{1000} \right) + 2 \times \left( \frac{700}{1000} \right) \times I_m = 2.4 \times I_m.$$  

The above three equations show that three multiple peaks occur in $P - V$ curves. Figures 9 and 10 represent the shading pattern and simulation results, respectively, for case-III. After reconfiguration the tier currents are as follows:

$$I_{R1} = \left( \frac{700}{1000} \right) + \left( \frac{600}{1000} \right) + \left( \frac{800}{1000} \right) \times I_m = 2.8 \times I_m,$$

$$I_{R2} = \left( \frac{500}{1000} \right) + \left( \frac{700}{1000} \right) + \left( \frac{900}{1000} \right) \times I_m = 2.8 \times I_m,$$

$$I_{R3} = \left( \frac{600}{1000} \right) + \left( \frac{500}{1000} \right) + \left( \frac{800}{1000} \right) + \left( \frac{900}{1000} \right) \times I_m = 2.8 \times I_m.$$  

Since all the tier currents are equal, a single global peak occurs in the $P - V$ curve. As the overall current increases in the array, the corresponding output power also enhances. The global peak power for the asymmetrical case at standard test condition is 2744 W. The maximum global power generated by TCT configuration and proposed configurations is 1781 W and 1916 W, respectively. Therefore the power is enhanced by 7.58% compared to fixed TCT configuration. The fill factor and the
### TABLE 4 Performance indices of PV array for TCT and MMTES based TCT under different cases

| Cases | Configuration | % Mismatch losses | Fill factor | Performance ratio | Efficiency |
|-------|---------------|-------------------|-------------|-------------------|------------|
| I     | TCT           | 45.6              | 0.598       | 54.3              | 13.2       |
|       | MMTES         | 40.1              | 0.769       | 59.8              | 14.54      |
| II    | TCT           | 48.48             | 0.566       | 51.5              | 12.28      |
|       | MMTES         | 40.59             | 0.727       | 59.4              | 14.16      |
| III   | TCT           | 35.09             | 0.621       | 64.9              | 13.5       |
|       | MMTES         | 30.17             | 0.76        | 69.8              | 14.52      |
| IV    | TCT           | 57.3              | 0.367       | 42.61             | 10.6       |
|       | MMTES         | 42.2              | 0.74        | 57.7              | 14.41      |

**FIGURE 7** Shading pattern for case-II

**FIGURE 8** $P - V$ curves for case-II

**FIGURE 9** Shading pattern for case-III

**FIGURE 10** $P - V$ Curves for Case-III

Performance ratio are enhanced by 22.5% and 7.5%, respectively, compared to conventional TCT configuration.

Case-IV:

Figure 11 shows the shading pattern to ensure that the global peak occurs on the left side of the $P - V$ curve during multiple peaks. It happens mostly when the irradiances are very low in one tier and the irradiance in one tier is very high. The tier currents corresponding to fixed TCT are given in Equations (27)–(29).

$$I_{R1} = \left( \frac{900}{1000} + \frac{900}{1000} + \frac{900}{1000} \right) \times I_w = 2.7 \times I_w,$$

(27)
Before reconfiguration, since tier currents are different from each other, three different peaks occur in the $P-V$ curve. After reconfiguration, as the difference in tier currents are very small, the $P-V$ curve appears like a single peak curve. Figure 12 shows the simulation results for case-IV. During traditional TCT interconnection, the MPPT algorithm gets trapped at a local peak, causing the reduction of the output power. However, after reconfiguration, conventional MPPT algorithm can track the global peak. In this case, the efficiency is improved by 35.94%, and mismatch losses are reduced by 26.35% compared to conventional TCT configuration.

Results show the reduction of multiple peaks and mismatch losses with the proposed algorithm. The performance parameters of the proposed method and the traditional TCT are compared and summarised in Table 3. As the global output power increases in all the cases, the performance ratio, fill factor and efficiency increase with the proposed configuration as summarised in Table 4. However, the implementation of the proposed algorithm for DPVAR requires several switches and sensors for the higher size PV array.

5 | HARDWARE RESULTS AND COST ESTIMATION ANALYSIS

5.1 | Hardware results

The effectiveness of the proposed arrangement was validated using a hardware prototype. In the experiment, the $P-V$ characteristics before and after reconfiguration under different shading conditions are configured using a PV simulator (Chroma 62050H-600S programmable DC power supply). A single-phase hall effect voltage and current sensors are used to sense the PV array voltage and current. The MPPT algorithm is implemented using Texas Instruments DSP TMS320F28335 to provide a PWM signal to the Boost converter. The experimental tests are performed under a scaled-down rating, as mentioned in Table 5.

The experimental setup of the proposed system is shown in Figure 13. The initial and final duty ratio is selected as 0.1 and 0.8, respectively, while the perturbation size is chosen as 0.025 in order to execute the conventional P&O MPPT algorithm.
Figures 14 and 15 show the experimental results of voltage, current and power for partial shading case-I before and after reconfiguration using a P&O algorithm. The conventional TCT scheme produces 86.4 W. After reconfiguration, the maximum power produced is 93.6 W. As a result, the maximum power is boosted to 7.2 W compared to the conventional configuration. Figure 16 represents the power, voltage and current for case-II before reconfiguration. The conventional TCT scheme produces an output power of 81.4 W. After reconfiguration, the corresponding voltage, current and power are shown in Figure 17. The reconfiguration scheme produces an output power of 96.2 W. Maximum power has been enhanced to 14.8 W.

Figures 18 and 19 show the voltage, current and power response for case-III. The conventional scheme generates an output power of 136.9 W. But the proposed algorithm produces 148.9 W, which is 8.76% higher compared to the conventional scheme. Figures 20 and 21 show the response during case-IV. In this case, the conventional algorithm produces an output power of 43 W. After reconfiguration, the maximum power is 92.60 W. The maximum power has been enhanced by 115% compared to
the conventional configuration. Figure 22 indicates the MPPT performance without reconfiguration for case-IV. During this case, the conventional P&O MPPT algorithm tracks the local peak. So, it is evident from Figure 22, a powerful optimisation-based MPPT is required to track the global peak. Figure 23 represents the MPPT performance for case-IV with dynamic array reconfiguration. The P&O algorithm is able to track the global maximum, with the proposed DPVAR.

Results of the conducted experiments strongly reinforce that the proposed algorithm efficiently track the global MPPT with simple MPPT algorithm under any complex partial shading conditions.

5.2 | Cost estimation analysis

The 10 KWp power generation using the proposed method for 3 × 3 PV array requires 54 switches, nine irradiance sensors and micro-controller. The fixed cost for conventional TCT configuration requires only PV panels if wiring cost is neglected.

| FIGURE 19 | Experimental results for partial shading case-III with reconfiguration |
| FIGURE 20 | Experimental results for partial shading case-IV without reconfiguration |
| FIGURE 21 | Experimental results for partial shading case-IV with reconfiguration |
| FIGURE 22 | MPPT performance for partial shading case-IV without reconfiguration |
| FIGURE 23 | MPPT performance for partial shading case-IV with reconfiguration |
### Table 5: Solar panel specifications for hardware

| Parameters | Values |
|------------|--------|
| $V_{oc}$   | 13.86 V |
| $I_{sc}$   | 1.64 A |
| $V_{mp}$   | 11.84 V |
| $I_{mp}$   | 1.55 A |
| Area       | 1.57 m² |

### Table 6: Cost of components for the proposed method

| S.no | Item                  | Sub components              | Cost ($) |
|------|-----------------------|-----------------------------|----------|
| 1    | PV panels             |                             | 6323.27  |
| 2    | Irradiance sensors    | Mini solar cell             | 3.79     |
|      |                       | Current sensor (ACS 723)    | 34.79    |
|      |                       | Temp. sensor (LM350)        | 11.934   |
|      |                       | Arduino Nano                | 29.52    |
|      |                       | Others                      | 0.5      |
| 3    | Switches              | Mosfet (IRF 640)           | 24.84    |
|      |                       | Heat Sink                   | 13.5     |
|      |                       | TLP 250                     | 83.7     |
|      |                       | Others                      | 0.5      |
| 4    | Controller            | Arduino                      | 11.98    |

The installation cost for conventional TCT configuration is $6323.27. The proposed algorithm requires additional hardware which may cost around $215.05.

The cost analysis of the proposed system is shown in Table 6. The cumulative electrical output produced by DPVAR for $q$ years is given as [30]

$$E_c(q) = E_c(q-1) + E_a \left( 1 - \frac{DF_u}{100} \right) + E_s \left( 1 - \frac{DF_s}{100} \right),$$

(33)

where $E_c(q-1)$ is the cumulative electrical output at the end of the $(q-1)$ years, $E_a$ and $E_s$ are the annual electrical outputs during shaded and unshaded condition. $DF_u$ and $DF_s$ are the derating factors of the PV plant under unshaded and shaded condition. The following assumptions made the $DF_u = 0.8\%$, $DF_s = 1.1\%$, $q = 6$ years and per unit cost is $0.107. Assume that the average irradiance available for power generation in a day is six hours. Among these six hours, each three hours are considered for shading and PSC, respectively. The maximum power output generated before and after reconfiguration of the TCT are determined using simulations for all the shading conditions. From the maximum power generated, the energy output is determined for these cases. Based on Equation (33), the cumulative electrical output generated is determined for $q$ years during all the cases and are presented in Table 7. Based on the electrical output, per unit cost and the initial cost, the payback period is determined and shown in Table 8. It is observed that the payback period is less compared to the conventional configuration, although the initial cost is slightly high. The income generated with respect to the number of years of the proposed and conventional approach is shown in Figure 24.

### Table 7: Comparison for electrical output energy generated for six years

| Cases | TCT (kW h) | MMTES (kW h) |
|-------|------------|--------------|
| I     | 96,917.54  | 101,964.87   |
| II    | 138,946.7  | 143,109.7    |
| III   | 91,273.26  | 100,644.6    |
| IV    | 98,648.42  | 102,135.4    |

### Table 8: Comparison for payback period

| Cases | TCT                      | MMTES                   |
|-------|--------------------------|-------------------------|
| I     | Three years, eight months| Three years, seven months|
| II    | Three years, six months  | Three years, seven months|
| III   | Three years, eleven months| Three years, eight months|
| IV    | Three years, seven months| Three years, seven months|

### 6 Conclusion

An MMTES algorithm is proposed for DPVAR to mitigate the effect of PSC on the performance of the PV array. The algorithm is built on tier-equalisation and can able to determine the optimal connection of switches, which delivers maximum output power. The performance of the proposed technique is compared and analysed with the fixed TCT configuration. PV parameters indices show the efficacy of the proposed algorithm compared to the conventional TCT configuration under different Partial shading cases. During the case-I and case-II, the algorithm removes and minimises the multiple peaks in the $P-V$ curve. Case-III proves that it can work for the unsymmetrical PV array. During case-IV, the algorithm significantly enhances the output power, which is quite useful for several PV applications. Further, the experimental results confirm and demonstrate that the proposed algorithm offers better output than...
the TCT configuration, and conventional MPPT is sufficient to track the global peak.

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