Shade dispersion methodologies for performance improvement of classical total cross-tied photovoltaic array configuration under partial shading conditions

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Abstract

Large size photovoltaic (PV) systems face a large number of issues based on malfunction and unfavourable climatic conditions such as partial shading conditions (PSCs). These PSCs are the major causes of PV systems’ performance degradation. In this paper, a symmetric matrix (SM) game puzzle is used to reconfigure the electrical connections of the PV array system. Present shade dispersion methodology is based on the ‘physical reallocation of PV module-fixed electrical connections’ principle. Modification in the electrical connections of conventional total cross-tied (TCT) PV array configuration introduces a new ‘SM-TCT’ configuration. An extensive comparative study of conventional TCT and novel-TCT (NTCT) configurations with proposed SM-TCT configuration prove the effectiveness to achieve higher performance. The MATLAB/Simulink results are obtained on the basis of the non-linear nature of current-voltage and power-voltage characteristics. SM-TCT, Shape-do-Ku, NTCT and TCT configurations are examined under three realistic PSCs in terms of power and voltage at global maximum power point, improved fill factor, reduced power losses, performance ratio and power enhancement.

1 | INTRODUCTION

Clean energy sources are gaining significant importance across the world due to various advantageous features such as economic, reutilisation, non-polluting and so forth. Among all the renewable energy sources, solar power is considered a primary power generation source in various domestics and commercial applications [1, 2]. It is observed that the advancement in solar energy technology is a regular process since the last decade. A photovoltaic (PV) module has very less efficiency as well as it is incompetent to assist the high load requirement [3]. Consequently, the methodology of the electrical connection is favoured to supply higher power demands. The connections of PV panels can be permitted to arrange in parallel or series. To raise power supply to a load, diversity in interconnections schemes like series–parallel (SP), bridge-linked (BL), total cross-tied (TCT) and honeycomb (HC) are implemented for the investigation during the partial shading conditions (PSCs) [4].

After several instances, the research work took shape due to unexpected failure conditions of the solar cell under PSCs. An intensive study is presented in reference to the accuracy, robustness, efficiency, execution and scope of application with discussion on strong and/or weak points of each method.

In [4], 9 × 4 size PV array configurations, for example, SP, TCT and BL, were executed. In addition to it, the behavioural assessment of considered configurations was done with respect to minimum power losses (PLs) and fill factor (FF) and so forth. Current-voltage (I-V) and power-voltage (P-V) curves of the SP-configured PV array (10 × 90) were implemented to analyse the shading effect. Moreover, an experimental investigation was carried out to prove the system performance [5]. In [6], the authors have observed that the mismatch losses (MLs) of TCT configuration are observed as low, compared to SP and
BL connections. The MATLAB/Simulation of SP, BL and TCT array configurations (6 × 4, 9 × 4) is presented and scrutinised under distinct PSCs. It has been observed that TCT arrangement is more efficient among all PV array configurations [7, 8]. A comprehensive study on the performance assessment of the existing PV array configurations (5 × 3, 6 × 4, 2 × 2 sizes), for example, series, parallel, SP, BL, TCT and HC were considered for the numerous shading scenarios in [9–15]. In [16], the authors investigated the performance of MATLAB/Simulink-based 4 × 4 sizes SP, TCT and BL interconnections under moving shading patterns. The TCT interconnection is found to produce more power as related to others under PSCs. The authors of [17] investigated 3 × 4 sizes SP and TCT interconnections for monitoring the effect of PSCs. Also, the effects and/or advantages of bypass diode were investigated. The SP, TCT and BL array configurations of 2 × 4, 2 × 6, 3 × 3, 3 × 4, 4 × 2, 4 × 3, 4 × 4, 6 × 2 and 6 × 4 sizes were considered to investigate the execution during 15 different random shading profiles [18]. The electrical performance of different configurations was evaluated for all the shading patterns. The 3 × 3 series sizes, parallel, SP and TCT PV array interconnections were investigated for the performance evaluation during distinct shading scenarios [19, 20]. The authors of [21–24] inspected the performance of all the existing PV array configurations, for example, series, parallel, SP, TCT, BL and HC, under numerous PSCs. Furthermore, the performance outcomes of considered patterns were analysed and compared side by side with 6 × 4, 5 × 4 and 9 × 9 PV array sizes. The authors of [25–27] designed 2 × 2 and 3 × 2 sizes electrical switch matrix-based SP array configuration for the extensive investigation under PSCs. Advanced and hybrid PV array arrangements, that is, SP-TCT and Su-do-Ku are realised for the investigation under obscured sun irradiance. In [28], the authors analysed the performance of SP, TCT, BL, non-symmetrical-1 (NS-1), non-symmetrical-2 (NS-2) and hybrid SP-TCT, BL-TCT interconnections of 5 × 4 sizes in of power aspects, for example, power and voltage at global maximum power point (GMPP), PLs and FF. The performance outcomes of NS-1 and NS-2 were found superior than conventional and hybrid configurations. In [29], the authors related the performance outcomes of TCT, hybrid configurations such as SP-TCT, BL-HC and BL-TCT with 4 × 4 size magic square configuration, which is found to be superior as higher power and voltage at GMPP, minimised PLs and improved FF. Moreover, conventional SP, BL, HC, TCT and reconfigured optimal TCT, NTCT PV array configurations were investigated under PSCs. Among all, suggested NTCT was characterised as having better performance [30–34]. In [35], the authors solved the issue of high length wire requirement for PV module interconnections during the reconfiguration methodology. The 9 × 9 size game puzzle scale, that is, dominance square (DS) puzzle, was used to reconfigure the PV array and compare it with standard SP and TCT configurations for predefined shading cases such as short wide (SW), long wide (LW), short narrow (SN) and long narrow (LN). The performance parameters were observed as GMPP location (4.647 kW), ML (3.453 kW), minimised PL (0.43 W) and improved FF (0.75) at 200, 400, 600 and 900 W/m² irradiation levels. In experimental study, an electromechanical relay system was utilised to switch from SP to TCT (3 × 3) configuration remotely for achieving higher GMPP power and voltage, minimum PL and improved FF under radiation levels as 380–710 W/m² [36]. Efficiency evaluation is the most required performance parameter along with GMPP, ML, and FF of solar PV configurations, which is evaluated improved Su-do-Ku game puzzle-based modified TCT connections. Moreover, an extensive comparative study was carried out under shadow test cases. The improved Su-do-Ku arrangement enhanced the GMPP by 26.9%, 30.3%, 30.8%, 16.8%, 4.2% and 6.3% as compared to the existing SP, BL, HC and TCT and Su-do-Ku arrangement of PV array [37]. Shade dispersion (SD) behaviour of shading conditions reduced the impact on PV array output. A novel approach, that is, odd-even (OE) methodology was carried out to arrange PV module in existing TCT connection for the reconfiguration. A comprehensive comparative study was carried out under four realistic shading cases. Proposed OE configuration has the highest performance parameters as 30.88%, 14.31%, 8.47% and 2.18% as compared to the existing SP, BL and TCT configurations [38]. In [39], improved power at GMPP as 22.36%, 43.36% and 39.31% for different shading cases was observed because of the adoption of a new skyscraper puzzle for the PV array reconfiguration. Moreover, the comparative investigation was carried out with DS game puzzle-based PV array configuration output performance index parameters such as ML, FF and PL. Performance of existing TCT and Su-do-Ku configuration was observed under LW, SN and SW shadowing test cases. Along with conventional PV configuration such as SP, TCT, HC, BL and hybrid BL-HC, BL-TCT and SP-TCT, the authors introduced ladder (LD) configuration for the performance evaluation under obscured irradiation levels from 300–1000 W/m². The efficient performance index output such as open-circuit (OC) voltage, short-circuit (SC) current, maximum voltage, current and power, PL, ML and FF were investigated and found that the hybrid and LD-based configurations were best in performance during all PSCs [40–42].

The above researches review motivate to compare the existing TCT, NTCT and novel symmetric matrix (SM)-TCT arrangement of PV array systems. The executions of suggested configurations are compared with classical TCT, NTCT PV array configurations. Considering all the specific PSCs, an extensive study finds that the novel SM-TCT configuration has better performance.

The major contributions of the innovative PV array configuration are emphasised as follows:

1. The SM-TCT interconnections of PV panels are adopted for achieving higher SD over the area covered by the PV array.
2. In accordance with the SD effect, the momentous minimisation of shadow on PV modules in any row is found and the power and voltage at GMPP is enhanced as compared to TCT, NTCT and Shape-do-Ku configurations.
3. The comprehensive comparative study is carried out for MATLAB/Simulink and experimental validation.
FIGURE 1 Electrical circuit diagram of a photovoltaic (PV) cell

| Parameters                      | Values |
|--------------------------------|--------|
| PV module power ($P_m$)        | 170 W  |
| Open-circuit (OC) voltage      | 44.2 V |
| Short-circuit (SC) current     | 5.2 A  |
| Current at maximum power point (MPP, $I_m$) | 4.75 A |
| Voltage at MPP ($V_m$)         | 35.8 V |

Moreover, the performance assessment of key parameters is analysed through P-V and I-V characteristics in terms of GMPP locations (voltage and power), FF, power enhancement (PE) under three distinguish realistic PSCs.

2. PV SYSTEM MODELLING AND GAME PUZZLES-BASED CONFIGURATIONS

Modelling schemes utilised during the planning of work is described in the section below:

2.1 PV system modelling

To design the PV array systems, different PV modules are arranged through interconnections in distinct methodologies, that is, serial and parallel to boost the power demand for higher rating load [29]. The identical electrical current diagram of a PV cell is depicted in Figure 1.

The voltage of a PV cell ($V_C$) is articulated through Equation (1) as

$$V_C = \frac{AKT_C}{e} \ln \left( \frac{I_{ph} + I_O - I_C}{I_O} \right) - I_C \left( \frac{R_s + R_{Sh}}{R_s R_{Sh}} \right)$$

The specifications of a commercially available PV module (BP3170 PV) are required for MATLAB Simulation, which is depicted in Table 1.

Moreover, 16 numbers of 5 W commercial PV modules (SFTI18P5: Solar universe India) are used for the experimental study. The specifications are depicted in Table 2.

2.2 Conventional TCT configuration

The TCT PV array configuration arrangement is accomplished from SP arrangement by interconnecting cross-connections across individual row-column of the PV array [34]. The voltage generated by the PV array can be exhibited as the sum of all the voltages of ’$n$’ number of rows. Therefore, using Kirchhoff’s voltage law, it is expressed in Equation (2) as

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

Kirchhoff’s law is used for the current analysis at an individual node point of PV array and can be articulated as shown in Equation (3) as

$$I_{array} = \sum_{i=1}^{i=n} I_{(j,i)} - I_{(j+1,i)} = 0$$  \hspace{1cm} (3)

Actual sun irradiance intensity ($S_x$) is the main cause of generated PV module current ($I_m$), expressed in Equation (4). Irradiance at standard test conditions ($S_{STC}$) is 1000 W/m² at which $I_m$ achieves its maximum current as

$$I_m = \frac{S_x}{S_{STC}} I_{max}$$  \hspace{1cm} (4)

2.3 NTCT configuration

A simple and new scheme of PV modules replacement in classical TCT is designed here. The PV modules are further subjected to enlarge shade distribution under shading conditions. The recommended scheme of replacement of PV modules can be accepted in arrays of dimension very easily [34].

The first column element in classical TCT arrangement are kept in the similar column for the proposed NTCT configuration as shown in Figure 2.

The elements of the first column in the classical TCT arrangement of PV array persist in the similar column of the suggested NTCT configuration. In the recommended configuration, the PV modules arranged in the first row of the classical TCT arrangement are reorganised as diagonal elements. All
the PV modules in addition to the first row are reconfigured among each other. The arrangements of PV modules of other row-columns are rearranged in the same position as shown in a zig-zag method. In this context, the configured scheme of 4 × 4 size PV modules arrangement in an array is implemented as per the recommended methodology. The PV modules presented in the first and third columns are reconfigured in a clockwise direction, whereas the PV modules of the second column are arranged in an anticlockwise manner. The PV modules, which are arranged in the progression of classical TCT arrangements are now located alternatively among the cells in NTCT. In this PV module replacement methodology, if any cell is engrossed, the successive cell is engaged. As per the recommended plan of PV module rearrangement, placement of PV module 22 is done by the module that is located at 32. Hereafter, the same has been allocated with the next subsequent location. The suggested arrangement scheme in [34] is shown in Figure 3.

2.4 Shape-do-Ku configuration

Shape-do-Ku puzzle is introduced in different dimension of symmetrical grids such as 4 × 4, 5 × 5 and 6 × 6. Shape-do-Ku puzzle, when compared to the Su-do-Ku puzzle, depicts similar property of not having additional outlined regions (such as the 3 × 2 boxes in the 6 × 6 Su-do-Ku puzzle). Thus, it is concluded that the Shape-do-Ku puzzle does not show any technical resemblance with Su-do-Ku but a variation of Latin square, puzzles with the only condition that each number appears at least once in each row and column [43]. The electrical arrangement of 4 × 4 size Shape-do-Ku puzzle-based PV array is depicted in Figure 4.

2.5 SM-TCT configuration

SM is a rational cyclic arrangement of integer numbers placed in a matrix. This matrix is special, as the sum obtained by the numbers of every row and column results in the same in all the cases. In addition to it, either of the diagonal element repeats within itself. All the properties of the 4 × 4 size SM are shown in Figures 5(a)–(d).

According to SM properties, it is noticed that the sum of all the elements of an individual row/column is 10. Moreover in Figure 5(d), the repetition of 2 × 2 size square sub-matrices also exist. The first digit of an individual PV module depicts
the count of rows wherein the second digit depicts the number of columns of $4 \times 4$ size PV array.

In Figure 6, the PV module positions are relocated using the suggested SM-TCT arrangement without undergoing any change in the electrical interconnections of the PV panels under PSCs. It is implemented such that module 12 (first row, second column) is physically rearranged on the first row and second column as shown in Figure 5(c). A similar methodology is adopted to arrange modules 32 (third row, second column) and 22 (second row, second column) as an example for achieving this novel SM-TCT arrangement.

For the placement of elements in order of $(j \times k)$, the $nth$ element can be stored corresponding to $j$th row and $k$th column, and $n_{jk}$ can be written as shown in Equation (5).

\[
  n_{jk}, \text{ where } \begin{cases} j = \text{no.of row} (j = 1, 2, ..., 4) \\ k = \text{no.of column} (k = 1, 2, ..., 4) \end{cases} \quad (5)
\]

On implementing Equations (5)–(7), the SM-TCT arrangement of PV array is attained.

(i) Summation: Row elements

The mathematical expression for four different types of conditions in row-wise summation are presented in Figure 4(a) and implemented through Equation (6) as

\[
  \sum_{k=1}^{4} n_{jk} = \text{Summation for } j\text{th row} \quad (j = 1, 2, 3, 4) \quad (6)
\]

(i) Summation: Column elements

The mathematical expression for four different types of conditions in column-wise summation are presented in Figure 4(b) and implemented through Equation (7) as

\[
  \sum_{j=1}^{4} n_{jk} = \text{Summation for } k\text{th column} \quad (k = 1, 2, 3, 4) \quad (7)
\]
3 | PERFORMANCE PARAMETERS AND ANALYSIS OF SHADING PATTERNS

All the PV modules in an array have distinguished MPP due to PSCs. Furthermore, the generated power is bypassed from partially shaded PV modules due to bypass diode utilisation to enhance the system performance. Maximum power point (MPP) tracking algorithm always misleads because of the existence of local MPP and GMPP because of the shading effect. P-V and I-V curves are used to observe performance parameter PSCs and are depicted in Figure 7.

Under PSCs, the total summation of maximum power produced by each PV module is denoted by the possible GMPP generated under the uniform solar irradiation. The maximum power produced by the array without shading effect is always higher than the power generated under PSCs, which defines PL as expressed in Equation (8).

\[
\text{PL} = \text{GMP under uniform irradiation} - \text{GMP under non-uniform irradiation} \tag{8}
\]

3.1 | Fill factor

The SC current and OC voltage without load are obtained from the behaviour of P-V and I-V curves. The ratio of maximum power to product of solar cell SC current and OC voltage is termed as FF. The PL occurs because the shading also affects the FF value; as a result, the significant decay in the GMPP under PSCs is found. The assessment of FF can be done using Equation (9).

\[
\text{FF} = \frac{V_{\text{mpp}} I_{\text{mpp}}}{V_{\text{oc}} I_{\text{SC}}} \tag{9}
\]

3.2 | Analysis of shading patterns

In this paper, three simple cases of PSCs are considered for the investigation. Figures 8(a)–(c) shows the considered partial shading cases, which are more suitable and likely to appear in a 4 × 4 size PV array [34]. In the MATLAB/Simulink model, shading test cases for TCT, NTCT, Shape-do-Ku and SM-TCT arrangements are considered in the solar irradiance level of individual PV module. For MATLAB/Simulink study, two types of irradiation levels such as 1000 and 500 W/m² are considered. Moreover, irradiation levels such as 790 W/m² (uniform) and 460 W/m² (shaded) are measured for extensive analysis during the experimental study.

4 | RESULTS AND DISCUSSION

The recommended configuration of the PV array is considered for the investigation under three different types of shading cases. The MATLAB simulation and experimental analysis for GMPP locations of TCT, NTCT, Shape-do-Ku and SM-TCT configurations in the PV array are evaluated. The GMPP location can be estimated through the current proximately in the individual row of PV array and is expressed in Equation (10):

\[
I_{\text{r}(i)} = \sum_{k=1}^{4} K_{i,k} I_{j,k} \tag{10}
\]
In Equation (11), \( K_{j,k} \) depicts solar irradiance for the panels denoted as \((j,k)\).

\[
K_{j,k} = \frac{G_{j,k}}{G_{STC}} \tag{11}
\]

where \(G_{j,k}\) is the solar irradiance of the PV module denoted as \(j, k\), and \(i_{j,k}\) is the generated current by the \((j,k)\)th panel. Generated current from all the PV modules under STC is supposed to be \(I_m\). Therefore, theoretical aspect of the generated currents in TCT configuration under shading case-I is shown in Equations (12) and (13) as

\[
I_{r1} = I_{r2} = I_m + I_m + I_m + 4I_m = 4I_m \tag{12}
\]

\[
I_{r3} = I_{r4} = 0.5I_m + 0.5I_m + 0.5I_m + 0.5I_m = 2I_m \tag{13}
\]

Thus, generated current in different rows are not the same amount due to PSCs. Neglecting all the tiny imbalances in the voltage observed across PV array, it is expressed as \(V_{array} = 4 \times V_n\). Moreover, the PV array-generated power is given in Equation (14) as

\[
P_{array} = V_{array} \times 4I_m \tag{14}
\]

for all the PV modules receive uniform solar irradiation, and none of the rows are bypassed. In NTCT, Shape-do-Ku and SM-TCT arrangements, the current across each row of PV array is calculated for shading case-I and is expressed in Equations (15)–(24) as follows:

\[
I_{r1} = I_m + 0.5I_m + I_m + I_m = 3.5I_m \tag{15}
\]

\[
I_{r2} = 0.5I_m + I_m + 0.5I_m + 0.5I_m = 2.5I_m \tag{16}
\]

\[
I_{r3} = I_m + 0.5I_m + I_m + I_m = 3.5I_m \tag{17}
\]

\[
I_{r4} = 0.5I_m + I_m + 0.5I_m + 0.5I_m = 2.5I_m \tag{18}
\]
The generated current in each row of Shape-do-Ku configuration is given as

\[ I_{r1} = I_{r2} = 0.5I_m + I_m + 0.5I_m + I_m = 3I_m \]  \hspace{1cm} (19)\]

\[ I_{r3} = I_{r4} = I_m + 0.5I_m + I_m + 0.5I_m = 3I_m \]  \hspace{1cm} (20)\]

The generated current in each row of SM-TCT configuration is given as

\[ I_{r1} = I_m + I_m + 0.5I_m + 0.5I_m = 3I_m \]  \hspace{1cm} (21)\]

\[ I_{r2} = I_m + 0.5I_m + 0.5I_m + I_m = 3I_m \]  \hspace{1cm} (22)\]

\[ I_{r3} = 0.5I_m + 0.5I_m + I_m + I_m = 3I_m \]  \hspace{1cm} (23)\]

\[ I_{r4} = 0.5I_m + I_m + I_m + 0.5I_m = 3I_m \]  \hspace{1cm} (24)\]

PE validation is found successful in all the recommended NTCT, Shape-do-Ku and SM-TCT arrangements under three shading test cases. The extensive evaluations are then established by obtaining their simulation responses in MATLAB/Simulink and experimental studies.

The theoretical power assessment is done on the basis of row current and voltage produced by the TCT, NTCT, Shape-do-Ku and SM-TCT arrangements in the three different PSCs. In this context, theoretical assessments to show the improved power of the SM-TCT configuration in comparison to the classical TCT configuration are shown in Table 3 under shading case-I. Similarly, power analysis can be done for the rest of NTCT and Shape-do-Ku configurations under shading cases II and III.

### TABLE 3  Theoretical power analysis of symmetric matrix (SM)-total cross-tied (TCT) configuration with respect to TCT configuration under shading case-I

| Shadowcase | Row no. | \( I_{row} \) | \( V_{array} \) | \( P_{array} \) | Advantage |
|------------|---------|---------------|----------------|----------------|-----------|
| 1          | 4       | \( I_4 \)     | 2\( I_m \)     | 4\( V_m \)     | 8\( I_m V_m \) | Uniform shade dispersion |
| 3          | 3       | \( I_3 \)     | 2\( I_m \)     | 3\( V_m \)     | 6\( I_m V_m \) | found in |
| 2          | 2       | \( I_2 \)     | 4\( I_m \)     | 2\( V_m \)     | 8\( I_m V_m \) | |
| 1          | 1       | \( I_1 \)     | 4\( I_m \)     | \( V_m \)      | 4\( I_m V_m \) | |
| 1          | 4       | \( I_4 \)     | 3\( I_m \)     | 4\( V_m \)     | 12\( I_m V_m \) | |
| 3          | 3       | \( I_3 \)     | 3\( I_m \)     | \( V_m \)      | 6\( I_m V_m \) | |
| 2          | 2       | \( I_2 \)     | 2\( I_m \)     | 2\( V_m \)     | 9\( I_m V_m \) | |
| 1          | 1       | \( I_1 \)     | \( I_m \)      | \( V_m \)      | 6\( I_m V_m \) | SM-TCT |

The TCT configuration experiences a large number of shading losses because of the lack of coherence between the module’s maxima power and GMPP of the PV array. In shading case-I, the GMPP of the TCT configuration is 1452 W at two different irradiation levels such as 1000 and 500 W/m². In NTCT, Shape-do-Ku and SM-TCT configurations, the GMPPs are found as 1781, 1831 and 1983 W, respectively. The performance output of the considered PV array configurations is contrasted on the basis of the smoothness of the P-V curves under shading situations.

During shading case-II, the TCT configuration experiences low performance in the aspect of power at GMPP as 2025 W. For similar climatic conditions (1000, 500 W/m²), NTCT, Shape-do-Ku and SM-TCT configurations have different locations of GMPPs such as 2209, 2209 and 2349 W, respectively.

Observation of power at GMPP is assessed through the existence of multiple maxima points on P-V characteristics. Under the shading case-III, power at GMPPs is observed for TCT, NTCT, Shape-do-Ku and SM-TCT configurations as 1601, 1832, 1832 and 1982 W, respectively. Due to SD property, SM-TCT configuration has the highest power at GMPP among the considered PV array configurations.

4.1 | MATLAB/Simulink analysis: P-V and I-V characteristics

A comprehensive study on the achieved performance of TCT, NTCT, Shape-do-Ku and SM-TCT configurations is deliberated. In ideal conditions, MPP is obtained as 2720 W. The behaviour of the obtained P-V curves for PV array configurations is analysed under shading cases I–III and are shown in Figures 9(a)–(c).
4.2 | Experimental analysis: P-V and I-V characteristics

An experimental study on $4 \times 4$ size of TCT, NTCT, Shape-do-Ku and SM-TCT configurations is performed. In ideal/uniform irradiation conditions (790 W/m$^2$), maximum power is achieved as 62.39 W. The investigation on PV system configurations is deliberated under similar shading cases I to III. The experimental setup is shown in Figure 11. The major components of the experimental setup are $4 \times 4$ size PV array system, variable load resistance and data logger (self-designed). The data logger system comprised voltage and current sensors to measure real-time electrical data (current and voltage) during the experimentation. The open-source Arduino system (ATmega-328 microcontroller) operated the system performance and stored the data in a micro SD card for future analysis.

An extensive experimental study on shading impact is carried out and the obtained electrical performance of TCT, NTCT, Shape-do-Ku and SM-TCT configurations is deliberated. The P-V curves for all the four PV array configurations are obtained under shading cases I-III as shown in Figures 12(a)–(c).

The TCT configuration experiences a large number of shading losses due to the lack of coherence between the power maxima point of PV modules in an array. In shading case-I, the GMPP of the TCT configuration is 38.24 W at distinguished irradiation levels of 790 and 410 W/m$^2$. Moreover, the GMPPs are found as 45.43, 44.55 and 48.68 W for NTCT, Shape-do-Ku and SM-TCT configurations, respectively. The performance of the considered PV array configurations is evaluated based on the smoothness of P-V curves under PSCs.

Under shading case-II, it is noticed that the TCT configuration has a low power level at GMPP as 45.47 W. Moreover, for similar non-uniform irradiance conditions (1000, 500 W/m$^2$), NTCT, Shape-do-Ku and SM-TCT configurations have different locations of GMPPs such as 52.48, 52.48 and 55.46 W, respectively.

Oblique-based shading case-III is considered for the performance evaluation of TCT, NTCT, Shape-do-Ku and SM-TCT configurations. The power at GMPP is assessed through
the existence of multiple maxima points on P-V characteristics. Powers at GMPPs are observed for all the considered PV array configurations such as 39.56, 45.43, 45.43 and 48.68 W, respectively.

Effect of irradiation level affects the SC current of the solar PV system. The I-V characteristics of TCT, NTCT, Shape-do-Ku and SM-TCT arrangements during the non-uniform irradiance levels for the distinct three considered shading cases of PV array are shown in Figures 13(a)–(c). For shading case-I, the I-V characteristic of the SM-TCT arrangement has no fluctuations as compared to the classical TCT arrangement. After considering all the PSCs, the obtained SC current of SM-TCT is found to be smaller as compared to the other configurations. The values of SC current are observed for the entire PV array configuration such as 1.737, 1.556, 1.556 and 1.375 A, respectively.

Under shading case-II, it is investigated that the I-V characteristic of SM-TCT arrangement is smoother as compared to other PV array configurations. The obtained values of SC current and OC voltage are found as 1.737 A and 44.2 V, respectively. The values of SC current for TCT, NTCT and Shape-do-Ku configurations are found as 1.737, 1.737 and 1.556 A, respectively. NTCT and Shape-do-Ku have more fluctuation due to shading impact.

In shading case-III, the nature of I-V characteristic of SM-TCT is found smoother as compared to TCT, NTCT and Shape-do-Ku configurations. Evaluation of SC current is carried out for all the PV array configurations and obtained as 1.55, 1.54, 1.54 and 1.37 A, respectively.
4.3 | Power and voltage at GMPP

The assessment of obtained power at GMPP is done and represented in Figure 14. The highest power at GMPP is obtained as 1983, 2349 and 1982 W for SM-TCT configuration under shading cases I–III, respectively, during MATLAB/Simulink study. Moreover, higher power at GMPP is obtained, that is, 48.68, 55.46 and 48.68 W for SM-TCT as compared to classical TCT, NTCT and Shape-do-Ku configurations under shading cases I–III, respectively, during the experimental study.

The voltage at GMPP is a very important parameter for delivering power to the load. In MATLAB/Simulink study, the voltage at GMPP for TCT, NTCT, Shape-do-Ku and SM-TCT configurations have distinguishing values under shading case-I (147.3, 145.3, 146.4 and 140.2 V), case-II (106.7, 147.7 and 142.3 V) and case-III (107.7, 145.8, 145.8 and 141 V).

During the experimental study, the voltage at GMPP for TCT, NTCT, Shape-do-Ku and SM-TCT configurations have distinguishing values under shading case-I (39.34, 38.7, 38.64 and 37.68 V), case-II (27.91, 38.95, 38.95 and 37.68 V) and case-III (40.07, 38.76, 38.76 and 37.68 V). Bar chart representation of voltage at GMPP is observed for the extensive analysis and shown in Figure 15.

4.4 | Power losses

PLs due to shading effect on PV systems such as TCT, NTCT, Shape-do-Ku and SM-TCT are observed for MATLAB/Simulink and the experimental studies. It is observed that SM-TCT configuration has minimum PLs of 27.09%, 11.43% and 27.13% under shading cases I–III.

In the experimental study, PLs observation is done and found that SM-TCT has values of 21.97%, 11.10%, and 21.97% during similar all three shading cases. Reduced PLs are observed for the SM-TCT configuration as shown in Figure 16.

4.5 | Fill factor

Dissimilarities in the FF due to the different shading cases for the TCT, NTCT, Shape-do-Ku and SM-TCT arrangements are computed and compared using the bar chart in
FIGURE 13  
(a)–(c) I-V characteristics of TCT, NTCT, Shape-do-Ku, SM-TCT configurations under PSCs.

FIGURE 14  
(a) and (b) Power at global maximum power point (GMPP) for experimental study.

FIGURE 15  
(a) and (b) Voltage at GMPP.
Figure 17. During shading cases I–III under MATLAB/Simulink study, SM-TCT has improved FF as 72.18%, 73.12% and 72.14%, respectively.

Assessment of FF is done and found that SM-TCT has the highest values of 79.55%, 80.09% and 79.55% for the experimental study under similar shading cases.

Critical analysis of P-V and I-V curves for both simulation and experimental studies are done under the shading cases I–III. During the study, realistic shading patterns such as double row shading, single row shading and oblique shading have a deep impact on the performance of solar PV array configurations. The behaviour of P-V and I-V curves reflects the quantitative analysis in terms of power and voltage at GMPP, PLs, FF and performance ratio. The obtained results for MATLAB/Simulink and the experimental study are depicted in Tables 4 and 5, respectively.

### TABLE 4 MATLAB/Simulink-based quantitative analysis of PV array configurations under three partial shading conditions (PSCs)

| Case   | Novel NCT (NTCT) | Shape-do-Ku | SM-TCT | TCT | Case   | Novel NCT (NTCT) | Shape-do-Ku | SM-TCT | TCT | Case   | Novel NCT (NTCT) | Shape-do-Ku | SM-TCT | TCT |
|--------|------------------|-------------|--------|-----|--------|------------------|-------------|--------|-----|--------|------------------|-------------|--------|-----|
|        |                  |             |        |     |        |                  |             |        |     |        |                  |             |        |     |
| Power at global MPP (GMPP; W) | 1452 | 1781 | 1831 | 1983 | 2025 | 2209 | 2209 | 2349 | 1601 | 1832 | 1832 | 1982 |
| Voltage at GMPP (V) | 147.3 | 145.3 | 146.4 | 140.2 | 106.7 | 147.7 | 147.7 | 142.3 | 107.7 | 145.8 | 145.8 | 141 |
| $V_{OC} (V)$ | 171.7 | 176.1 | 176.1 | 176.1 | 174.1 | 176.5 | 176.5 | 176.5 | 173.9 | 176.1 | 176.1 | 176.1 |
| $I_{SC} (A)$ | 20.8 | 18.2 | 18.2 | 15.6 | 20.8 | 20.8 | 20.8 | 18.2 | 18.2 | 18.2 | 18.2 | 15.6 |
| Power loss (PL; W) | 1268 | 939 | 889 | 737 | 695 | 511 | 511 | 311 | 1119 | 888 | 888 | 738 |
| $P_{in}(\%)$ | 46.61 | 34.52 | 32.68 | 27.09 | 25.55 | 18.78 | 18.78 | 11.43 | 41.13 | 32.64 | 32.64 | 27.13 |
| Fill factor (FF; \%) | 40.65 | 55.56 | 57.12 | 72.18 | 55.91 | 60.17 | 60.17 | 73.12 | 50.58 | 57.16 | 57.16 | 72.14 |
| Power enhancement (PE; \%) | – | 18.47 | 20.69 | 26.77 | – | 8.32 | 8.32 | 13.79 | – | 12.60 | 12.60 | 19.22 |
| Best configuration | SM-TCT | SM-TCT | SM-TCT |

FIGURE 17 (a) and (b) Fill factor assessment under PSCs
TABLE 5  Experimental study-based quantitative analysis of PV array configurations under three PSCs

| Case-I | Case-II | Case-III |
|--------|---------|----------|
|        | TCT     | NTCT     | Shape-do-Ku | SM-TCT | TCT     | NTCT     | Shape-do-Ku | SM-TCT | TCT     | NTCT     | Shape-do-Ku | SM-TCT |
| Power at GMPP (W) | 38.24  | 45.43  | 44.55  | 48.68  | 45.47  | 52.48  | 52.48  | 55.46  | 39.56  | 45.43  | 45.43  | 48.68  |
| Voltage at GMPP (V) | 39.34  | 38.7   | 38.64  | 37.68  | 27.91  | 38.95  | 38.95  | 37.68  | 40.07  | 38.76  | 38.76  | 37.68  |
| \(V_{OC} (V)\) | 43.8   | 44.5   | 44.5   | 44.5   | 44.2   | 44.5   | 44.5   | 44.5   | 44.2   | 44.5   | 44.5   | 44.5   |
| \(I_{SC} (A)\) | 1.737  | 1.556  | 1.556  | 1.375  | 1.737  | 1.737  | 1.737  | 1.556  | 1.554  | 1.54   | 1.54   | 1.375  |
| PL (W) | 24.15  | 16.96  | 17.84  | 13.71  | 16.92  | 9.91   | 9.91   | 6.93   | 22.83  | 16.96  | 16.96  | 13.71  |
| \(P_{loss} (\%)\) | 36.70  | 27.18  | 28.59  | 21.97  | 21.17  | 15.88  | 15.88  | 11.10  | 36.59  | 27.18  | 27.18  | 21.97  |
| FF (%) | 50.26  | 65.61  | 64.33  | 79.55  | 59.22  | 67.89  | 67.89  | 80.09  | 57.74  | 66.29  | 66.29  | 79.55  |
| PE (%) | –  | 15.82  | 14.16  | 21.44  | –  | 13.35  | 13.35  | 21.97  | –  | 12.92  | 12.92  | 18.73  |
| Best configuration | SM-TCT | SM-TCT | Shape-do-Ku | SM-TCT | SM-TCT | SM-TCT |

FIGURE 18  (a) and (b) Power enhancement assessment under PSCs

4.6  | Power enhancement

PE is the increase in power produced by the reconfigured PV array system because of the shading dispersion and can be expressed in Equation (25) as

\[
PE = \frac{\text{GMPP}_{\text{SM-TCT}} - \text{GMPP}_{\text{TCT}}}{\text{GMPP}_{\text{SM-TCT}}}
\]  

Equation (25)

Assessment of PE is carried out with MATLAB/Simulink and experimental studies. During shading cases I–III, SM-TCT has the highest PE with respect to TCT configuration such as 26.77%, 13.79% and 19.22%, respectively.

Furthermore, PE is observed as 21.44%, 21.97% and 18.73% during the experimental study. Bar chart representation for PE is shown in Figure 18.

5  | CONCLUSION

This paper analysed and compared the performance of conventional TCT, NTCT with new Shape-do-Ku and SM-TCT configurations under realistic PSCs. The method used is a simplified reconfiguration technique, can be extended to any size of the PV array, and performance is assessed under key parameters such as PL, PE, and FF with comprehensive comparative MATLAB/Simulink and experimental studies.

Thus, the proposed reconfiguration scheme for PV modules is particularly advantageous for the design of large PV farms. From the results’ analysis, it is clear that the novel SM-TCT configuration has a lower number of power maxima points. The key points of both the studies are as follows:

1. For case-I: The performance parameters such as power at GMPP, FF, PE (w.r.t. TCT) and reduced PLs are found best as 1983 W, 0.72, 26.77% and 737 W, respectively, for SM-TCT configuration through MATLAB/Simulation study under shading case-I. During experimental validation, similar performance parameters are observed and found as 48.68 W, 0.79, 21.44% and 13.71 W.

2. Overall, SM-TCT has the best values during MATLAB/Simulink and experimental studies under shading cases II and III.

The present study will be beneficial for commercial PV plants and new beginners in this area as a standard for future research work.

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APPENDIX

The MATLAB/Simulink diagram for symmetric matrix (SM) total cross-tied (TCT) photovoltaic (PV) array configuration and a unit PV module is shown in Figure A-1. For each PV module, two respective inputs, namely, irradiation and temperature are shown in Figure A-1. Dark colour input of the module indicates the partial irradiation (500 W/m²), and the white colour indicates the full irradiation level of (1000 W/m²).

**FIGURE A-1** MATLAB/Simulink model of SM-TCT configuration and unit PV module