Research article

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Improved performance of partially shaded photovoltaic array with reformed-total cross tied configuration

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Abstract: Renewable energy sources are receiving wide popularity due to the shortage of fossil fuels and environmental problems caused by conventional energy sources. Solar photovoltaic energy is a widely used sustainable energy source. The power developed by a solar cell is greatly influenced by the insolation level. Partial shading occurs when one or more photovoltaic (PV) cells receive lesser radiation as compared to other cells, which in turn affects the overall electrical performance of PV cells including reduced generated power. This paper proposes a newly developed configuration known as Reformed-Total cross-tied (R-TCT) to improve the power generation during partially shaded conditions in small-scale PV systems, especially for urban and rural area applications. The basic idea of this paper is to redistribute the shaded modules of a row to other rows such that the number of shaded solar PV modules of each row are nearly same. The proposed method is validated by simulation and also by hardware implementation. The simulations and experiments are done on eight different shading cases and found that the proposed method gives either superior or same performance as that of existing TCT, LS (Latin Square)-TCT, and D-TCT configurations.

Keywords: partial shading issue; power improvement; PV array reconfiguration; solar energy; total cross tied configuration.

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Introduction

The ever-increasing requirement for electricity can be fulfilled by the use of Photo Voltaic (PV) technology, which is the conversion of solar energy into electricity with low carbon emission and without any moving parts (Ellabban, Abu-Rub, and Blaabjerg 2014). The generated power of a PV system is unpredictable due to the variation of atmospheric conditions (Yang, Zhou, and Lou 2009). Partial shading is a significant problem that causes a reduction in power generated by PV systems (Yang, Zhou, and Lou 2009). Residential PV systems in urban and rural areas are affected by partial shading with an annual performance loss of 10–20% (Hanson et al. 2014). Due to localisation of heat during partial shading, hot spots are created on PV modules, which can be avoided by using bypass diodes (Kim and Krein 2013; Reinoso, Milone, and Buitrago 2013). However, the use of bypass diodes will lead to the plurality in maximum power points in the electrical features of PV system (Ishaque, Salam, and Taheri 2011). The shadowing of PV array directly influences the power output and energy yield by minimising the reception of solar energy as well as hiking energy loss from the shaded cells. Even though we avoid partial shadings during the installation time, the chances of shading occurrences cannot be ruled out permanently, and so strategies for improving the generated power and enhancing performances of PV system are receiving great importance.

The two ways of limiting the reduction in power due to partial shading are (i) passive methods, and (ii) active methods (El-Dein, Kazerani, and Salama 2012). Connecting bypass diodes across the cells is the most commonly used passive method. However, a high economic inconsistency and practical difficulty are caused if bypass diodes are affixed across individual PV cell for gaining better performance under shading conditions (Roman et al. 2006). Hence, a single bypass diode for a group of cells is the normally accepted method. The electrical redesigning of PV array is the active method used in encountering shading issues (Wang and Hsu 2011).

PV arrays with requisite power capacity are derived by connecting the PV modules in series and parallel combinations. Classical interconnection methods are series (S), parallel (P), series-parallel (SP), total cross tied (TCT), honey comb (HC) and bridge link (BL) (Said et al. 2018). Combinations of these classical methods lead to the formation of hybrid configurations like SP-TCT, BL-TCT, and BL-HC (Yadav, Pachauri, and Chauhan 2015). TCT performs well in almost all shading patterns among the classical and hybrid methods. A rigid type interconnection method is adopted in rearranging the PV modules in an array to distribute the shading effects to minimise the shading losses (Rao, Ilango, and Nagamani 2014). In Moballegh and Jiang (2013), authors discussed the prediction and identification of global maximum power point (GMPP) under partial shading conditions. The Su Du Ko puzzle (Rani, Ilango, and Nagamani 2013) based rearrangement is developed to reduce the mismatch losses in PV arrays by distributing shading effects and this particular method is further modified to reduce the line losses during installation (Rao et al. 2015). A zig-zag arrangement (Vijayalekshmy, Bindu, and Iyer 2016) of PV modules in a PV array is analysed for different shading patterns including corner shading. The performance of zig-zag method is analysed by considering performance ratios and fill factor. In Pareek, Chaturvedi, and Dahiya (2017), interconnection laws are presented by making use of the comparison of SP and TCT configuration. Practical implementation of this method is difficult as it requires many sensors and switching circuits. A novel structure (NS) by physical relocation of PV modules is developed and the performance of this method is compared with classical TCT and hybrid TCT configurations for shading patterns including diagonal shading (Mishra et al. 2017). A magic square puzzle (Yadav et al. 2017) based physical reallocation of PV modules in SP, TCT, BL, and HC configurations is considered for vertical, horizontal, and diagonal shading. Position of GMPP, power losses and fill factors are used for analyzing and comparing the results. In Pachauri et al. (2018), Latin square puzzle based TCT arrangement is developed by the physical movement of PV panels for shading patterns including progressive shading and zig-zag shading. The physical relocation of PV modules, based on Latin square puzzle, performs better than the conventional TCT arrangement. An innovative technique of reconfiguration based on the 'chaotic baker map' (Tatabhatla, Agarwal, and Kanumuri 2019) image processing technique is proposed to minimise the power loss of partially shaded PV arrays and reduce the number of peak points. Recent work by (Madhanmohan, Nandakumar, and Saleem 2020) proposed a method known as diagonally dispersed total cross-tied configuration (D-TCT) which performs better than existing methods for most of the shading cases. On verification, it is found that a modification to this method is required for the cases where the shades are in the first two columns so as to generate maximum power.

From the literature review, it can be concluded that the existing methods need modification due to one or more of the following factors: (i) The implementation cost is high, (ii) requires complex thinking like solving puzzles, (iii) frequent movements of PV modules based on particular shading patterns. This paper presents an easily realisable and simple method known as Reformed Total Cross Tied (R-TCT) configuration to minimise the power losses caused by partial shadings on PV modules. In this method, the shaded modules are redistributed among other rows such that the goal of achieving nearly equal shaded modules in all rows is attained. In this work, a row means all the PV modules which are joined in parallel and not the physical row. Hence, there is no requirement that the physical locations of modules be changed as suggested in some papers. The method requires a special configuration of electrical connections, which can be done at the time of installation.

The remainder of this paper is arranged as follows: The partial shading issue is presented in Section 2. Section 3 discusses the modeling of PV configuration and factors affecting generated power. The proposed methodology is narrated in Section 4. Section 5 confers the numerical simulation and experimental results.

Problem formulation

Series and parallel arrangements of PV modules are the basics of PV array configuration. Let n be the number of unshaded PV modules, I_g be the generated current and V_g be the generated voltage of each module. Considering the case where all the n modules are unshaded, the current, voltage and generated power can be derived as

For series PV configuration,

$$I_{\text{array}} = I_{g1} = I_{g2} = I_{g3} = \dots\dots\dots\dots = I_{gn} = I_g \tag{1}$$

$$V_{\text{array}} = V_{g1} + V_{g2} + V_{g3} + \dots\dots\dots\dots + V_{gn} = nV_g \tag{2}$$

$$P_{\text{array}} = nV_g I_g \tag{3}$$

and for parallel PV configuration,

$$I_{\text{array}} = I_{g1} + I_{g2} + I_{g3} + \dots\dots\dots\dots + I_{gn} = nI_g \tag{4}$$

$$V_{\text{array}} = V_{g1} = V_{g2} = V_{g3} = \dots\dots\dots\dots = V_{gn} = V_g \tag{5}$$

$$P_{\text{array}} = nV_g I_g \tag{6}$$

For a general PV configuration with i rows and j columns

$$I_{array} = jI_g \quad (7)$$

$$V_{array} = iV_g \quad (8)$$

$$P_{array} = (i \times j)\, V_g I_g = nV_g I_g \quad (9)$$

For uniformly shaded condition with shading parameter S_f, the generated current of each module is reduced to $s_f I_g$. Neglecting the voltage drop across bypass diode, the generated voltage is same as V_g. Then the generated power is reduced to

$$P_{array} = S_f nV_g I_g \quad (10)$$

where,

$$S_f = \frac{g}{g_{STC}} \quad (11)$$

is the shading factor. g is the actual insolation and g_{STC} is the insolation at standard testing condition (1000 W/m^2). Equation (10) implies that partial shading causes a decrease in the generated power. The objective of this paper is to develop a methodology that guarantees an improvement in the generated power under partial shading conditions.

Modeling of PV array and factors affecting power generation

Modeling of PV array configuration

A PV module or PV panel is made by connecting a number of PV cells in series as shown in Figure 1. The shade on the panels signifies a major decrease in the energy produced by the cells (Kalogirou 2013). Shading on the panels leads to the formation of hot spots. To minimise the effects of hot-spots on PV panels, bypass diodes are connected in anti-parallel (He et al. 2015). Each PV cell might need one bypass diode for optimal efficiency. Since it is uneconomical, a single diode is usually fixed for a small number of series cells (Zheng et al. 2014). Figure 1 depicts the analogous circuit of a PV panel with a bypass diode. For a panel with a bypass diode, the generated current is given by

$$I_g = \left[I_{ph} - I_0 \left(e^{\frac{q(V_g + R_s I_{pv})}{AKTN_s}} - 1 \right) - \frac{V_g + R_s I_{pv}}{R_{sh} N_s} \right] + \left[I_{obypass} \left(\frac{-qV_g}{e^{AbypassKT}} - 1 \right) \right] \quad (12)$$

where, I_0 is reverse saturation current (A), q is the electron charge, A is a dimensionless material quantity, T is the temperature in Kelvin, V_g is the output voltage of the module (V), N_s is the number of solar cells in series, $I_{0bypass}$ is the reverse saturation current of bypass diode (A) (Varghese and Reji 2019; Vijayalekshmy, Bindu, and Iyer 2015). Table 1 gives the parameters of PV module used for the Matlab simulation.

Factors affecting generating power

The best choice of PV configuration depends on the type, pattern, location, and intensity of shading. The basic configurations used for interconnection of PV modules are (i) series (S), (ii) Parallel (P), (iii) Series-Parallel (SP), (iv) Bridge Linked (BL), (v) Honey comb (HC). Another approach to interconnection of PV modules is Total Cross Tied (TCT) configuration which is obtained from SP configuration as shown in Figure 2. Studies prove that TCT configuration is the best interconnection method among the available basic configurations, for reducing losses due to partial shading. Consider a TCT PV array with q rows and q columns.The voltage and currents of the array are represented by

$$V_{array} = \sum_{i=1}^{q} V_i \quad (13)$$

By Kirchhoff's current law, the current delivered by ith row can be expressed as

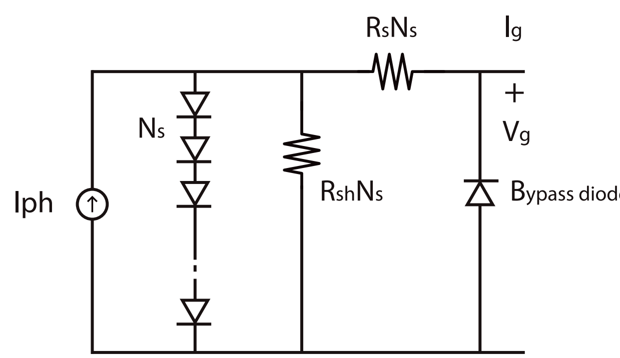


Figure 1: Circuit representation of PV panel with a bypass diode.

Table 1: Specifications of designed PV module used for simulation at 1000 W/m^2, 25 °C.

PV module parameters	Values
Maximum power	20.08 W
Open circuit voltage	21.1 V
Short circuit current	1.23 A
Current at MPP	1.145 A
Voltage at MPP	17.5 V

$$I_{\text{array}} = \sum_{j=1}^{q} I_{ij} \quad (14)$$

where I_{ij} is the current of PV module in ith and jth column. When the impact of solar insolation is taken into account, the current provided by a PV module is

$$I = S_f I_g \quad (15)$$

Under normal insolation condition, $g = g_{\text{STC}}$ and for a $q \times q$ TCT setup, the current provided by each row can be written as

$$I_{R_j} = qI_g, \quad \text{where}, j = 1, 2, 3, 4, \ldots \ldots \ldots .q \quad (16)$$

When m modules in a row are shaded, the row current can be calculated as

$$I_{R_j} = [mS_f + (q - m)]I_g \quad (17)$$

Neglecting the variations in the voltage drop across individual rows, Equation (13) can be used to calculate the PV array voltage.

$$V_{\text{array}} = qV_g \quad (18)$$

multiplying Equation (17) and (18) results in

$$P_{\text{array}} = qV_g I_g[(mS_f) + (q - m)] \quad (19)$$

In this work the analysis is accomplished by using a 4 × 4 PV array. Figure 2 shows representation of TCT configuration. Consider a case where three modules (say modules 11, 12, 13) are partially shaded. Let the insolation level be 60%, then by Equation (15) the currents generated by these modules are

$$I_{11} = I_{12} = I_{13} = \frac{600}{1000} I_g = 0.6I_g \quad (20)$$

and

$$I_{IJ} = I_g, IJ \neq 11, 12 \text{ and } 13 \quad (21)$$

Hence,

$$I_{R_1} = 2.8I_g, \text{ and} \quad (22)$$

$$I_{R_2} = I_{R_3} = I_{R_4} = 4I_g \quad (23)$$

The current supplied to the load is just $2.8I_g$, and the power is limited to $11.2V_gI_g$ since all the rows are connected in series. An improvement in the power can be achieved if the three shaded modules are connected in three separate rows. Let us connect module 12 in the second row, module 13 in the third row, and keep module 11 in the first row itself. It may be noted that modules in a row mean modules that are joined in parallel. As a result, each one of the shaded modules appears in the first, second, and third rows and so

$$I_{R_1} = I_{R_2} = I_{R_3} = 3.6I_g \quad (24)$$

then, the array current is then raised to $3.6I_g$, and the power to $14.4V_gI_g$. The number of shaded solar PV modules in a row is designated in this paper as row shading number, and the maximum among all row shading numbers is designated as maximum row shadings. In Table 2 N_{shj} is row shading number, N_m is maximum row shadings. Table 2 considers nine different shading patterns with diverse row shading numbers. The table illustrates that as N_m increases, power decreases. The same observation can be obtained from the PV characteristics as shown in Figure 3.

The above observation gives us an idea for the solution of partial shading effect which can be stated as redistributing of shaded modules of a row to other rows such that the maximum number of shaded modules of a row is decreased, gives an improved power. The proposed work utilizes this basic idea, which is discussed in next section.

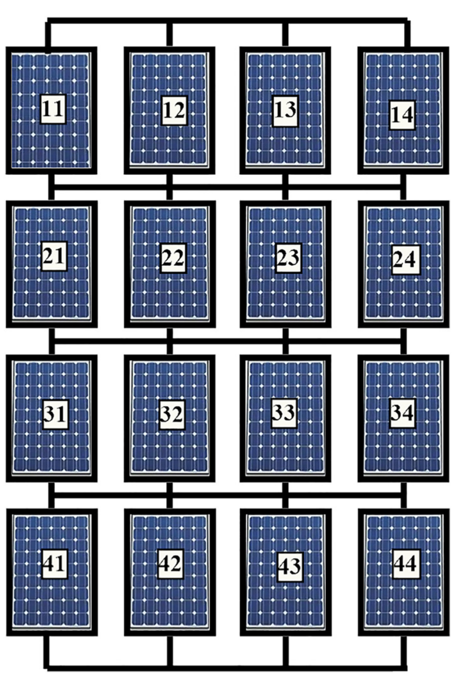


Figure 2: Representation of a 4 × 4 TCT PV array.

Proposed methodology

Let the PV array is arranged with n rows and n columns. Let the module at ith row and jth column of TCT is denoted by T_{ij} and that of RTCT is denoted by R_{ij}. Then the RTCT configuration is defined as follows:

Table 2: Effects of number of shaded solar PV modules in a row.

Case	Row shading number (N_{shj})				Maximum row shading	Row currents (A)				Array currents (A)	Array power (W)
	N_{sh1}	N_{sh2}	N_{sh3}	N_{sh4}	N_m	I_{R1}	I_{R2}	I_{R3}	I_{R4}		
1	0	0	0	0	0	$4I_g$	$4I_g$	$4I_g$	$4I_g$	$4I_g$	$16V_gI_g$
2	1	0	0	0	1	$3.6I_g$	$4I_g$	$4I_g$	$4I_g$	$3.6I_g$	$14.4V_gI_g$
3	2	0	0	0	2	$3.2I_g$	$4I_g$	$4I_g$	$4I_g$	$3.2I_g$	$12.8V_gI_g$
4	3	0	0	0	3	$2.8I_g$	$4I_g$	$4I_g$	$4I_g$	$2.8I_g$	$11.2V_gI_g$
5	4	0	0	0	4	$2.4I_g$	$4I_g$	$4I_g$	$4I_g$	$2.4I_g$	$9.6V_gI_g$
6	1	1	0	0	1	$3.6I_g$	$3.6I_g$	$4I_g$	$4I_g$	$3.6I_g$	$14.4V_gI_g$
7	1	1	1	0	1	$3.6I_g$	$3.6I_g$	$3.6I_g$	$4I_g$	$3.6I_g$	$14.4V_gI_g$
8	1	1	1	1	1	$3.6I_g$	$3.6I_g$	$3.6I_g$	$3.6I_g$	$3.6I_g$	$14.4V_gI_g$
9	4	4	4	4	4	$2.4I_g$	$2.4I_g$	$2.4I_g$	$2.4I_g$	$2.4I_g$	$9.6V_gI_g$

$$
\begin{aligned}
R_{jj} &= T_{1j}, j = 1, 2, 3, \ldots, n \\
R_{kj} &= T_{nj}, j = 1, 2, 3, \ldots, n \text{ and } k = n - j + 1 \\
R_{1j} &= T_{kj}, j = 2, 3, \ldots, n - 1, k = n - 1 \\
R_{2j} &= T_{kj}, j = 1, n, \text{ and } k = n - 1 \\
R_{nj} &= T_{kj}, j = 2, 3, \ldots, n - 1, k = 2 \\
R_{nj} &= T_{kj}, j = 1, n, \text{ and } k = 2
\end{aligned}
$$

For all other cases

$$R_{ij} = T_{ij}$$

It may be noted that only the electrical connections of modules are changed and their physical locations are unaltered. Using the above definition, any $n \times n$ PV array TCT configurations can be converted into an RTCT configuration. Figure 4(B) and (D) shows the RTCT congiguartion for 4 × 4 and 6 × 6 PV array configurations, respectively. A comparative performance of TCT and RTCT configurations in terms of the maximum power generated for a typical shading case can be analyzed from Figure 5(A) and (B) and it is obvious that RTCT performs well as compared to TCT.

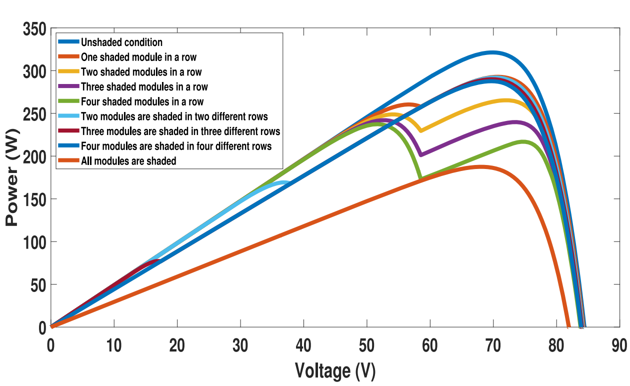


Figure 3: Comparison of maximum power for diverse number of shaded panels per row.

Results and discussions

This section addresses the results of a comparison analysis of the electrical performance of TCT, LS-TCT, D-TCT, and R-TCT arrangements in different cases. The shading patterns displayed in Figure 6 are considered for the study, which are selected based on a theoretical and practical point of view. In Case 1, three modules in the top corner of the array are shaded. Case 2 depicts the shading on the left bottom corner of a 4 × 4 PV array. Cases 3–8 depicts the most realistic shading situations. The shading cases for TCT and R-TCT configurations are shown in Figure 6, which are included in the relative analysis. All of the R-TCT structures in this figure depict a representative view of analogous electrical connection rather than the physical structure.

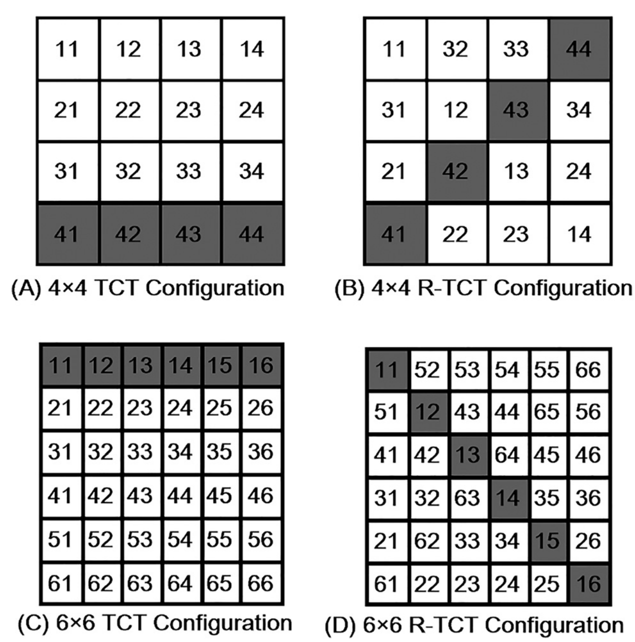
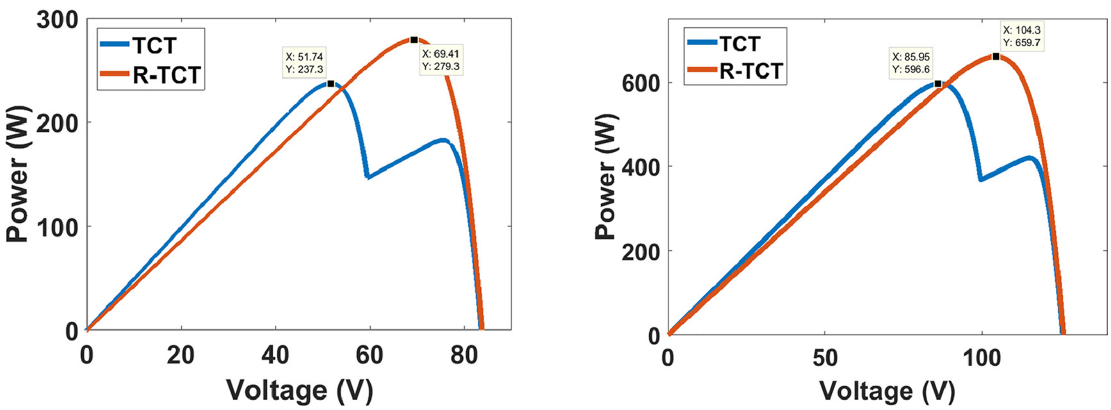


Figure 4: TCT and R-TCT arrangement for 4 × 4 and 6 × 6 PV array.



(A) Power Voltage Characteristics of 4×4 PV array

(B) Power Voltage Characteristics of 6×6 PV array

Figure 5: Power voltage charateristics for 4 × 4 and 6 × 6 PV array.

For these four configurations, the different shading patterns are analysed and studied. At a temperature of 25 °C, it is assumed that unshaded panels receive 1000 W/m^2 of insolation and shaded panels receive 500 W/m^2. Hence, as determined by Equation (15), the current generated by a shaded module is $0.5I_g$. The corresponding peak powers of TCT and proposed R-TCT configurations for eight different partially shaded conditions are given in Table 3.

Let c be the number of rows for which atleast one of the bypass diode is conducting,

$$V_{\text{array}} = (q - c)\,V_g \tag{25}$$

Consider TCT configuration Case 1 of Figure 6,
Case 1(a)

$$I_{\text{array}} = 3I_g \tag{26}$$

Then, no diodes are bypassed and hence;

$$c = 0\;;\; V_{\text{array}} = (q - c)\,V_g = 4V_g \tag{27}$$

$$P_{\text{array}} = 4V_g 3I_g = 12V_g I_g \tag{28}$$

Case 1(b)

Let $I_{\text{array}} = 3.5I_g$, Then row 1 will be bypassed and hence $c = 1$

$$V_{\text{array}} = (4 - 1)\,V_g = 3V_g \tag{29}$$
$$P_{\text{array}} = 3V_g 3.5I_g = 10.5V_g I_g \tag{30}$$

Case 1(c)

Let $I_{\text{array}} = 4I_g$, Then row 1 and row 2 are bypassed and hence $c = 2$

$$V_{\text{array}} = (4 - 2)V_g = 2V_g \tag{31}$$

$$P_{\text{array}} = 2V_g 4I_g = 8V_g I_g \tag{32}$$

For all other cases peak powers are calculated and tabulated in Table 4.

Comparison of maximum power generated

Figures 7 and 8 show the P-V and I-V characteristics of TCT, LS-TCT, D-TCT, and proposed R-TCT configurations. The maximum power for each case is marked in the P-V characteristics. For all the cases expect cases 3 and 4 being considered the proposed method generates the highest power. For case 3 maximum power generated for D-TCT is more compared to other methods. For case 4 the LS-TCT and D-TCT have equal performance. Figure 9 shows the comparison of maximum power generated for TCT, LS-TCT, D-TCT, and R-TCT.

Comparison of partial shading losses

Partial shading losses are defined as the difference between the maximum power generated under the standard testing condition to the maximum power generated for partial shading conditions (PSC).

$$\text{PSC}_{\text{losses}} = \text{MPP}_{\text{Standard testing condition}} - \text{MPP}_{\text{Partial shading condition}} \tag{33}$$

Here the maximum power generated for standard testing conditions for TCT arrangement of 4 × 4 PV array is 321.40 W. The PSC losses of TCT and RTCT are compared in Table 4. It is clear from the Table that the power losses are much reduced for the R-TCT arrangement. It is very clear from Figure 10 partial shading losses of the proposed R-TCT method are reduced by 36.2, 36.2, 78.5, 78.5, 78.5, and 72.10 W for the Cases 1, 2, 5, 6, 7, 8, respectively.

Performance ratio

The performance ratio of proposed PV array is obtained by Equation (34). The performance of proposed method can be compared with existing methods using a performance ratio.

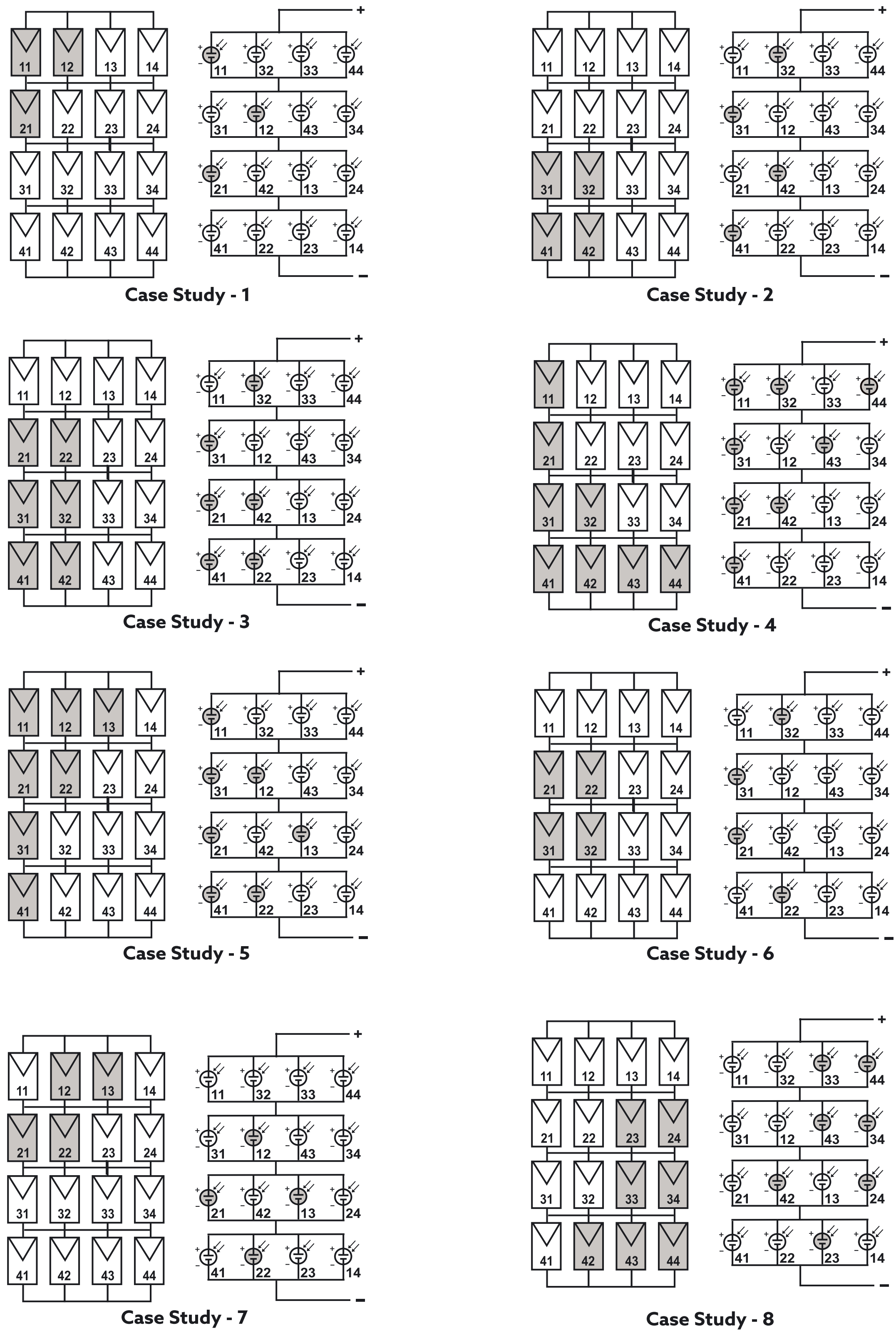


Figure 6: Representation of shading patterns in TCT and proposed configurations.

Table 3: Peak power calculations of shading patterns in Figure 6.

Cases	Type	Row 1	Row 2	Row 3	Row 4	Peak powers			
		I_{R1}	I_{R2}	I_{R3}	I_{R4}	Peak 1	Peak 2	Peak 3	Peak 4
Case 1	TCT	$3I_g$	$3.5I_g$	$4I_g$	$4I_g$	$12I_gV_g$	$10.5I_gV_g$	$8V_gI_g$	–
	R-TCT	$3.5I_g$	$3.5I_g$	$3.5I_g$	$4I_g$	$14I_gV_g$	$4V_gI_g$	–	–
Case 2	TCT	$4I_g$	$4I_g$	$3.5I_g$	$3I_g$	$12V_gI_g$	$10.5V_gI_g$	$8V_gI_g$	–
	R-TCT	$4I_g$	$3.5I_g$	$3.5I_g$	$3.5I_g$	$14V_gI_g$	$4V_gI_g$	–	–
Case 3	TCT	$4I_g$	$3I_g$	$3I_g$	$3I_g$	$12V_gI_g$	$4V_gI_g$	–	–
	R-TCT	$3.5I_g$	$3.5I_g$	$3I_g$	$3I_g$	$12V_gI_g$	$7V_gI_g$	–	–
Case 4	TCT	$3.5I_g$	$3.5I_g$	$3I_g$	$2I_g$	$8V_gI_g$	$9V_gI_g$	$7V_gI_g$	–
	R-TCT	$2.5I_g$	$3I_g$	$3I_g$	$3.5I_g$	$10V_gI_g$	$9V_gI_g$	$3.5V_gI_g$	–
Case 5	TCT	$2.5I_g$	$2.5I_g$	$3.5I_g$	$4I_g$	$10V_gI_g$	$7V_gI_g$	$4V_gI_g$	–
	R-TCT	$3.5I_g$	$3I_g$	$3I_g$	$3I_g$	$14V_gI_g$	$9V_gI_g$	–	–
Case 6	TCT	$2.5I_g$	$3I_g$	$3.5I_g$	$3.5I_g$	$10V_gI_g$	$9V_gI_g$	$7V_gI_g$	–
	R-TCT	$3.5I_g$	$3I_g$	$3I_g$	$3I_g$	$12V_gI_g$	$3.5V_gI_g$	–	
Case 7	TCT	$4I_g$	$3I_g$	$3I_g$	$2.5I_g$	$10V_gI_g$	$9V_gI_g$	$4V_gI_g$	–
	R-TCT	$3I_g$	$3I_g$	$3I_g$	$3.5I_g$	$12V_gI_g$	$3.5V_gI_g$	–	–
Case 8	TCT	$4I_g$	$3.5I_g$	$3I_g$	$2.5I_g$	$10V_gI_g$	$9V_gI_g$	$7V_gI_g$	$4V_gI_g$
	R-TCT	$3.5I_g$	$3I_g$	$3I_g$	$3.5I_g$	$12V_gI_g$	$7V_gI_g$	–	–

Table 4: Performance analysis.

Performance parameter	Type	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Maximum power generated (W)	TCT	262.8	262.8	186.6	187.9	212.5	218.7	217.8	220.1
	LS-TCT	262.8	262.8	187.9	237.3	217.8	242.9	242.9	245.3
	D-TCT	262.8	262.8	223.3	216.4	218.7	218.7	218.7	249.3
	R-TCT	285.2	285.2	187.9	237.3	242.9	242.9	242.9	249.3
Partial shading losses (W)	TCT	58.6	58.6	134.8	133.5	108.9	102.7	103.6	101.3
	LS-TCT	58.6	58.6	133.5	84.1	103.6	78.5	78.5	76.1
	D-TCT	58.6	58.6	98.1	105	102.7	102.7	102.7	72.1
	R-TCT	36.2	36.2	133.5	84.1	78.5	78.5	78.5	72.1
Performance ratio	TCT	81.77	81.77	58.06	58.46	66.12	68.05	67.77	68.48
	LS-TCT	81.77	81.77	58.46	73.83	67.77	75.58	75.58	76.32
	D-TCT	81.77	81.77	69.48	67.33	68.05	68.05	68.05	77.57
	R-TCT	88.74	88.74	58.46	73.83	75.58	75.58	75.58	77.57
Power enhancement	TCT	7.85	7.85	0.69	20.82	12.52	9.96	10.33	11.71

$$\text{Performance ratio}_{PV_{\text{array}}} = \frac{\text{Pmpp}_{\text{under partialshading conditions}}}{\text{Pmpp}_{\text{under uniform conditions at STC}}} \quad (34)$$

Percentage of power enhancement

Power enhancement ratio is the percentage increase in power produced by using proposed method of reconfiguration.

$$\text{Power enhancement} = \frac{\text{GMPP}_{\text{Proposed method}} - \text{GMPP}_{\text{Existing method (TCT)}}}{\text{GMPP}_{\text{Proposed method}}} \quad (35)$$

Performance ratios of TCT, LS-TCT, D-TCT, and R-TCT are compared in Table 4 and Figure 11. Improvements in the performance ratio when compared to TCT configuration are 6.97, 6.97, 9.46, 7.53, 7.81, and 9.09% for the Cases 1, 2, 5, 6, 7, 8.

The power enhancement of proposed with existing methods are given in Table 4. The percentage of power enhancement when compared TCT configuration are 7.85, 7.85, 0.69, 20.82, 12.52, 9.92, 10.33, and 11.71%.

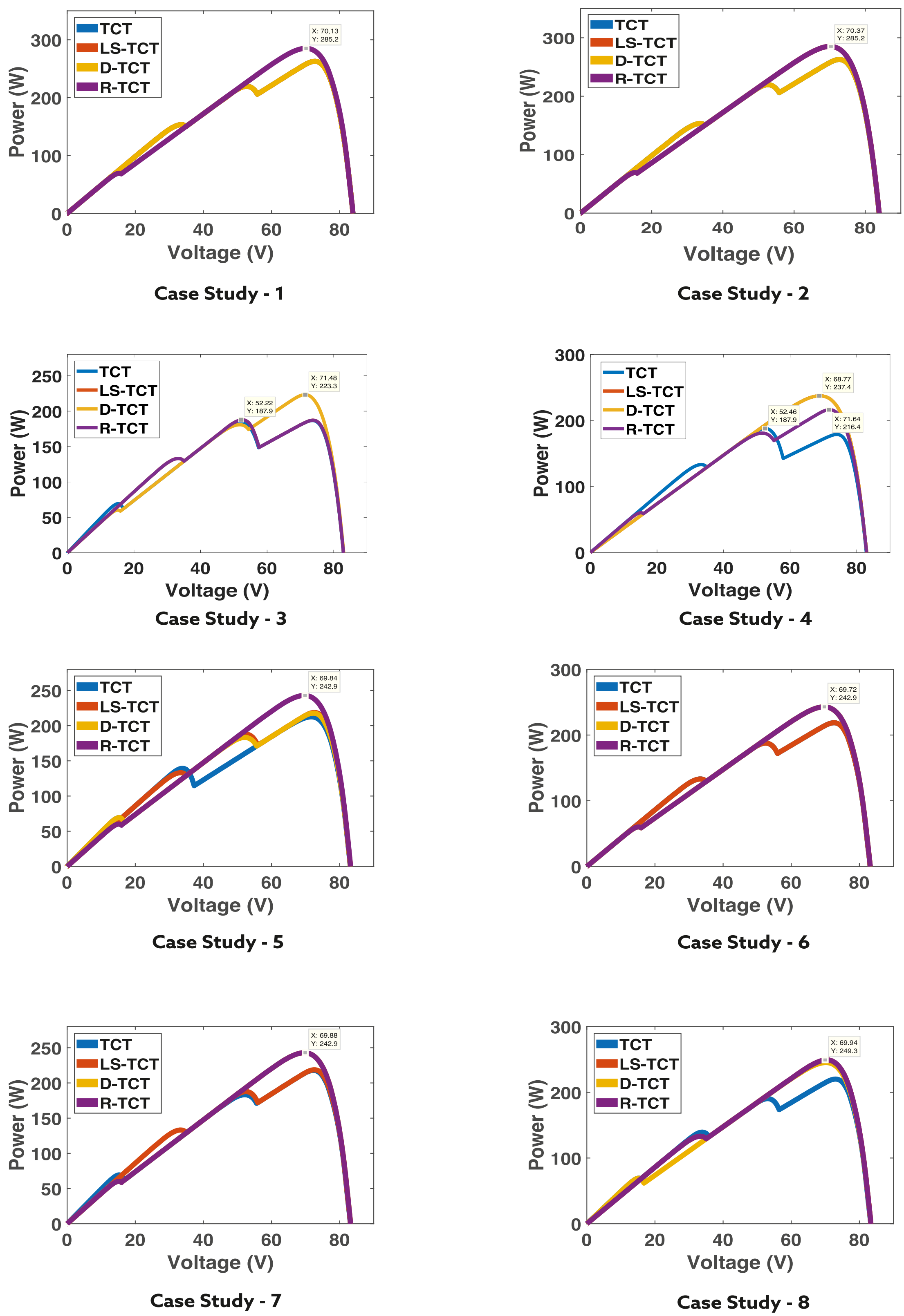


Figure 7: Power-voltage characteristics.

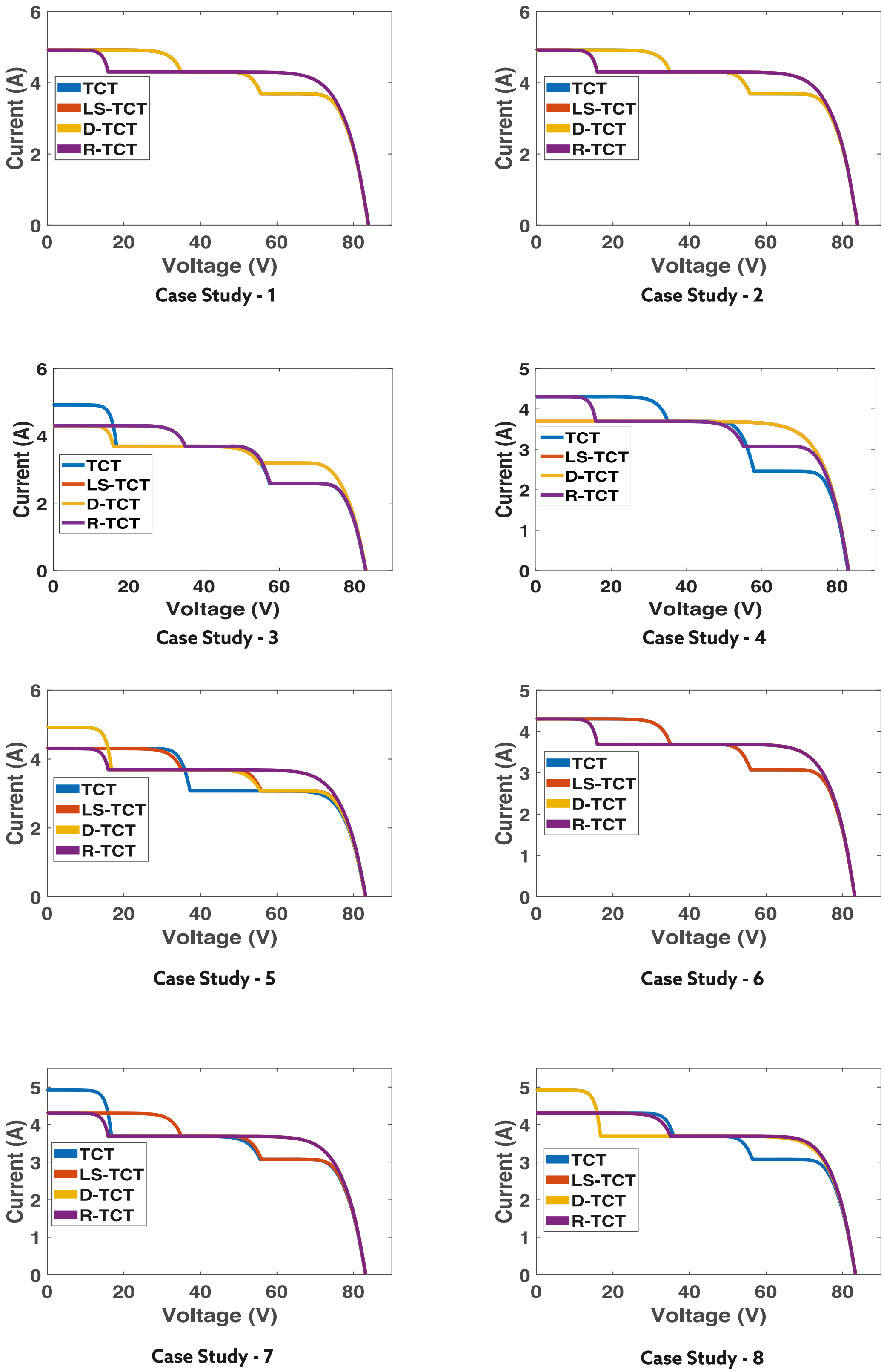


Figure 8: Current-voltage characteristics.

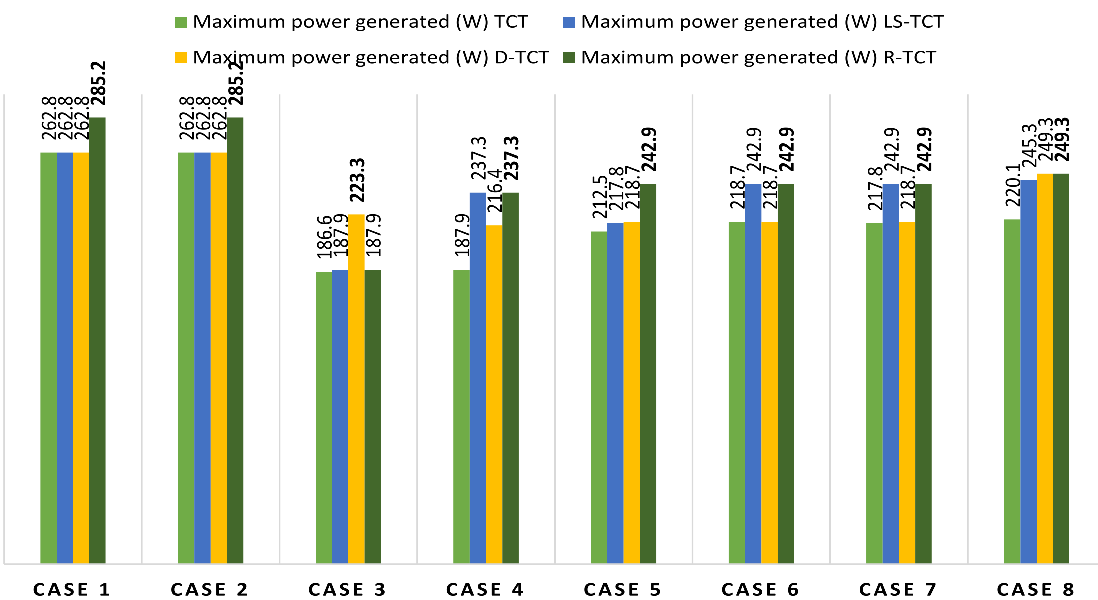


Figure 9: Comparison of maximum power generated.

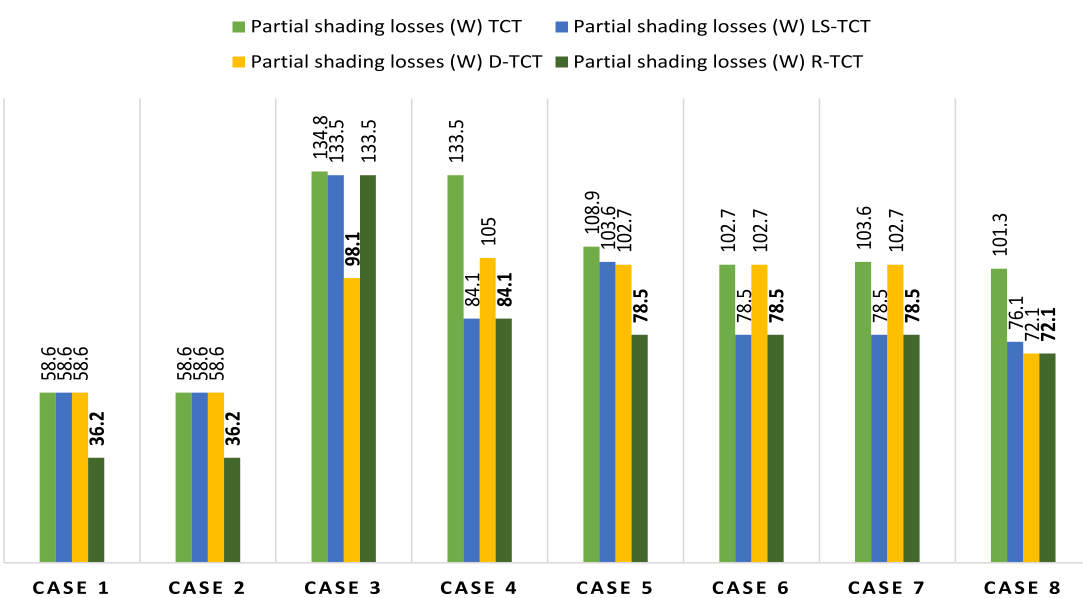


Figure 10: Comparison of partial shading losses.

Experimental results

The 4×4 PV array in the prototype field experiment is made up 16 of 20 W PV panels and connecting wires. Transparent sheets are used for creating the partially shaded conditions. The experimental setup for R-TCT configuration for Case 2 is represented in Figure 12. A variable rheostat is connected across the PV array as load. The experiment has been conducted on a particularly sunny day and irradiance is measured as 780 W/m^2 using a solar power meter and the temperature is measured as 35 °C using an infrared thermometer. The maximum power generated is calculated by

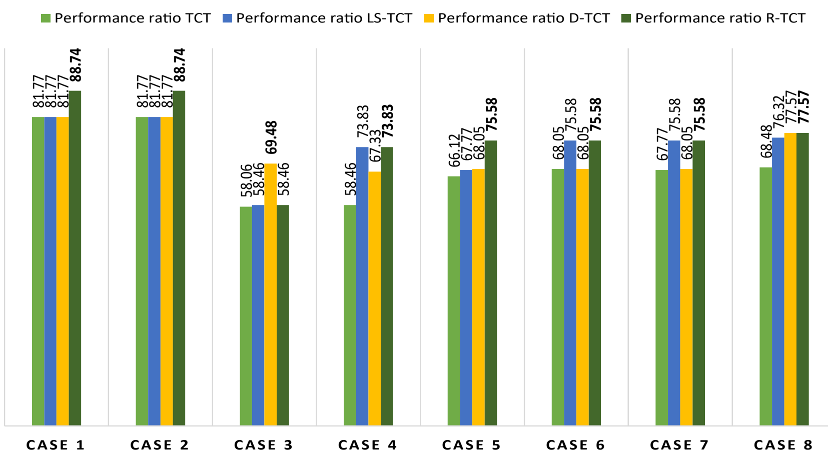


Figure 11: Comparison of performance ratio.

changing the load rheostat and power is measured using a power meter. The maximum power produced by TCT and R-TCT configurations is tabulated under almost the same irradiance conditions. Figure 13 compares the maximum power generated in TCT and R-TCT configurations during the experimental analysis. The results of experiments also demonstrate that the proposed R-TCT design performs well compared to basic TCT configurations.

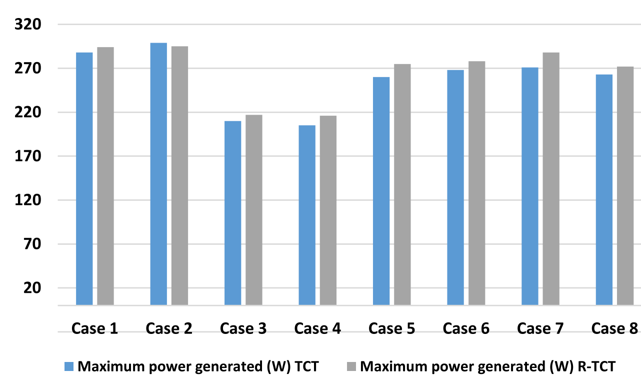


Figure 13: Comparison of maximum power produced.

Conclusion

This paper proposes a method known as Reformed-total cross tied (R-TCT) to reduce the power losses on PV arrays due to partial shading. The basic idea of this work is to achieve a nearly equal number of shaded modules on each group of the parallel connected cells of TCT connection and the method is applicable to any $n \times n$ PV array. The connections of the proposed configuration are made at the time of installation and do not require the physical relocation of modules for various shading conditions. This work considered eight different shading cases and verified the effectiveness of the proposed method, by both simulation and experiments. A comparative analysis is carried out using the performance parameters maximum generated power, partial shading losses, performance ratio and power enhancement ratio. Among the four configurations (TCT, LS-TCT, D-TCT, R-TCT) the proposed R-TCT gives best generated power for all cases of shadings being considered.

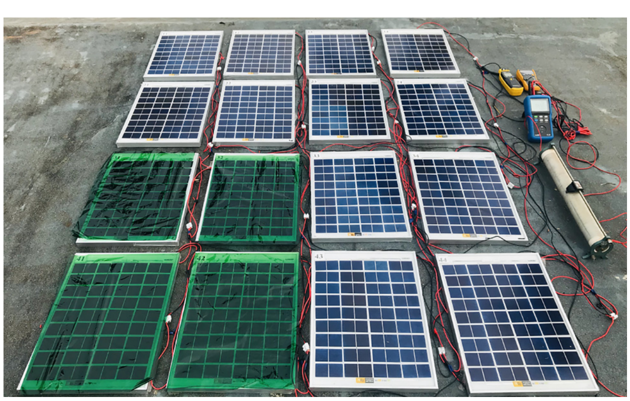


Figure 12: Experimental setup.

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