

Enhance the Output Power of a Shaded Solar Photovoltaic Arrays with Shade Dispersion based TCT Configuration

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Partial shading has a negative impact on the performance parameters of a Solar Photovoltaic (PV) array, because it shades certain panels while leaving others un-shaded. This article focuses on modeling, comparing and performance assessment of 6×6, 6×5 and 5×6 size shadowed solar PV arrays under different partial shading cases in the MATLAB/ Simulink software. For this purpose, the simulation of series-parallel (SP), Total-Cross-Tied (TCT) and proposed shade dispersion based TCT (SD-TCT) type of array configurations was carried out under few shading cases. The proposed SD-TCT was designed using the shades dispersion technique, which is based on a number logic approach. In this technique, in order to effectively remove the row-current mismatches in the TCT PV array configuration, the shaded and un-shaded modules in an array were re-arranged, so that the shading on modules expands across the whole array. The physical placement of the TCT array modules has been reordered in accordance with the proposed number logic pattern exclusive of altering the electrical links among the panels. The simulation results showed that the performance of the SD-TCT type was superior to that of conventional array configurations.

Keywords: PV Array; Modules; Configurations; Mismatch Losses; Power improvement; Shading Cases

Introduction

The power generated by solar photovoltaic (PV) plants varies with the temperature and irradiance of the PV module. Shades, such as shadows of surrounding trees, shifting clouds and dust deposition on modules, directly influence the cell temperature and radiation level of the PV system. In the shading conditions (SC), the power generated by the array is reduced and results in the output P-V curves to have multiple peaks *i.e.*, LMPP (Local maximum power point) and GMPP (Global maximum power point). Several MPPT tracking methods for LMPP and GMPP of the solar PV array configurations have been proposed in the literature. One solution for reducing losses from malfunction and shading is PV array configurations. The foremost conventional PV array configuration or arrangements or structures are Parallel-Series (SP), Bridge-Linked (BL), Series (S), Honey-Comb (HC), Parallel (P), Total-Cross-Tied (TCT) type. In the literature of [1-5], a brief comparison study among S, P, SP, TCT, and

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BL structures was conducted in the MATLAB/Simulink environment. The findings suggested that the design of TCT achieves the best output power under most SCs. A further alternative is the use of dynamic reconfiguration methods such as power electronics Equalizer (PEE) type and the electric array reconfiguration (EAR) methods to remove multiple peaks of the shaded array P-V-specifications and thus increase the power produced by an array. The solution is also proposed in the literature. But more sensors, switches, and control algorithms are essential for implementing the above techniques in an enormous PV farm [6-10].

In order to overcome this limit, it is suggested to adopt different static array reconfiguration methods, such as magic-square pattern, Sudoku and optimal sudoku pattern and Futoshiki puzzle pattern [11-12] to boost the power generation in SC and rearrange the TCT configuration with $i \times j$ size array (where i is no. of rows and j is no. of columns). In the above techniques, the optimum location of any module is calculated based on the shadow model to minimize the shading losses, and the PV panel is relocated without modifying the electrical links. Such techniques, however, refer only to a square type of PV arrays and not to non-square arrays, *i.e.*, $i \neq j$. For digit i , which is either odd or even number, the current study suggests a novel approach based on shade dispersion (SD-TCT) configuration of arrays $i=j$ and $i \neq j$. The proposed method for rearranging the row location of an $i \times j$ PV array is generalized in this context. In different shading conditions, a comparison is made of the SD-TCT configuration with different existing settings, including SP and TCT of an $i \times j$ ($i, j=6$ and 5) array. In the SD-TCT structure, the modules positions only need to be changed once during installation, *i.e.*, electrical links alteration of modules are unnecessary. Therefore, for the execution of the existing scheme in real time at a wide PV system, and it doesn't need a lot of switches, sensors, control algorithms. The proposed structure spreads the shadows across the PV array to ensure increased the array power under SC.

The rest paper is structured as modeling of a PV array, various array configurations, the methodology used in the proposed configuration, and the simulation, modeling and performance study of different size arrays.

Mathematical Modeling

Modeling of Photovoltaic Array

The PV cell transforms the light energy into electricity and increases the output voltage by the series of cells known as module or panel. The PV array is a grouping of the series (N_s) and parallel (N_p) connected panels, which are exposed in Figure 1.

The equations of 1, 2, and 3 are represented mathematically of a solar PV cell, module, and array [13-14], respectively.

$$I_{cell} = I_{ph} - I_0 \left[\exp \left\{ \frac{q(V_{cell} + I_{cell}R_{ser})}{KAT_c} \right\} - 1 \right] - \left[\frac{(V_{cell} + I_{cell}R_{ser})}{R_{par}} \right] \quad \text{--- (1)}$$

$$I_m = I_{ph} - I_0 \left[\exp \left(\frac{q(V_m + I_m R_{ser})}{n_s K A T_c} \right) - 1 \right] - \left[\frac{(V_m + I_m R_{ser})}{R_{par}} \right] \quad \text{--- (2)}$$

$$I_a = N_p \cdot I_{ph} - N_p \cdot I_0 \left[\exp \left(\frac{q(V_a + \frac{N_s}{N_p} I_a R_{ser})}{N_s K A T_c} \right) - 1 \right] - \left[\frac{(V_a + \frac{N_s}{N_p} I_a R_{ser})}{\frac{N_s}{N_p} \cdot R_{par}} \right] \quad \text{--- (3)}$$

where V_{Cell} and I_{Cell} , V_m and I_m , V_a and I_a are voltage[V] and current[A] of a solar PV cell, module and array, respectively. N_S and N_P are the no. of series and parallel connected modules, n_s is the no. of series connection pv cells, I_0 is reverse saturation current [A], I_{ph} is the photo-generated current [A], R_{ser} and R_{par} are series and parallel resistances[Ω], and a is the ideality factor. Cell thermal voltage is given as $V_{Th} = k T_C/q$, where q : Charge of electron, T_C : Cell operating temp, and k : Boltzmann's constant.

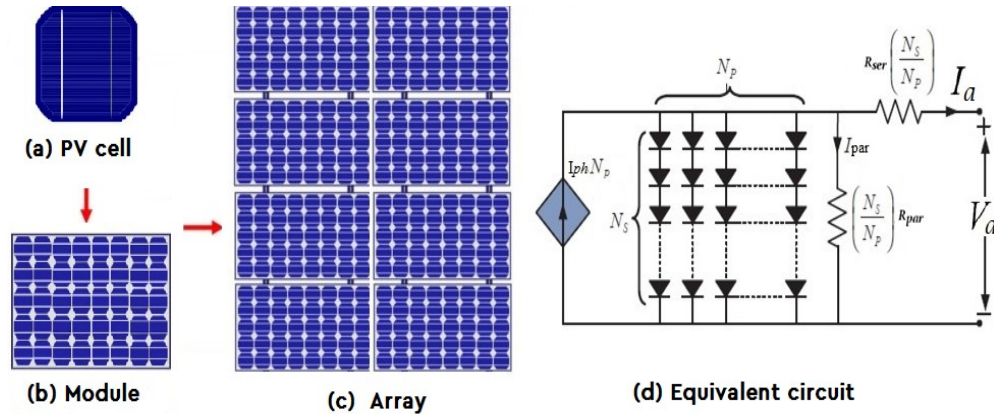


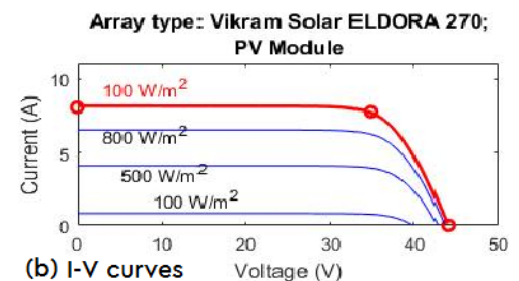
Figure 1. Solar PV array formation

Modeling of Photovoltaic Array

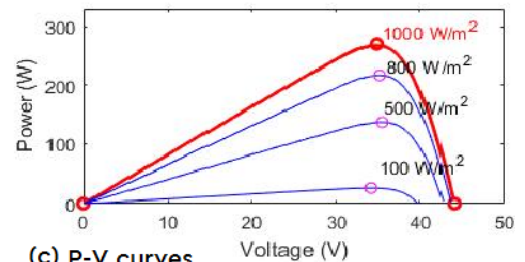
In this work, the Vikram Solar PV module is used for the simulation of SP, TCT, SD-TCT array arrangements. The specifications and output curves of module are shown in Figure 2.

Electrical Parameters		Values
Maximum Power		270 W
Cells per module	N_{cell}	72
Open circuit voltage	V_{OC}	44 V
Short-circuit current	I_{SC}	8.1 A
Voltage at maximum power point	V_{MP}	34.7 V
Current at maximum power point	I_{MP}	7.8 A
Temperature coefficient of V_{oc}		-0.3583% / $^{\circ}C$
Temperature coefficient of I_{sc}		0.0249% / $^{\circ}C$
Light generated current	I_L	8.1924 A
Diode saturation current	I_0	2.4871e-10
Diode ideality factor		0.98223
Shunt resistance	R_{sh}	3126.5623 Ω
Series resistance	R_s	0.52303 Ω

(a) Vikram Solar PV module parameters



(b) I-V curves



(c) P-V curves

Figure 2. Parameters and output curves of a solar PV module

Solar PV Array Configurations

The foremost traditional configurations are total-cross-tied (TCT), series (S), bridge-linked (BL), series-parallel (SP), honey-comb (HC), parallel (P) type of arrangements, as illustrated in Figure 3. The difference in row currents is created because of shaded conditions, and PV panels with lower irradiation are thus bypassed. Therefore,

many peaks are formed in the P-V output characteristics, and therefore some power is lost. PV array reconfigurations or rearrangements methods are used to spread the shade uniformly around the PV array, which can significantly reduce the mismatch losses (ML) in PV systems. Researchers have made numerous efforts to research and evaluate the shading effect on array configurations to minimize ML and to achieve maximum power production. In other words, the lower radiation PV module is relocated electrically or physically so that a single P-V peak is reached. This paper only considered SP, TCT, and proposed SD-TCT (re-arranged TCT connection) type of configurations for analyzing the performance of different sizes PV arrays.

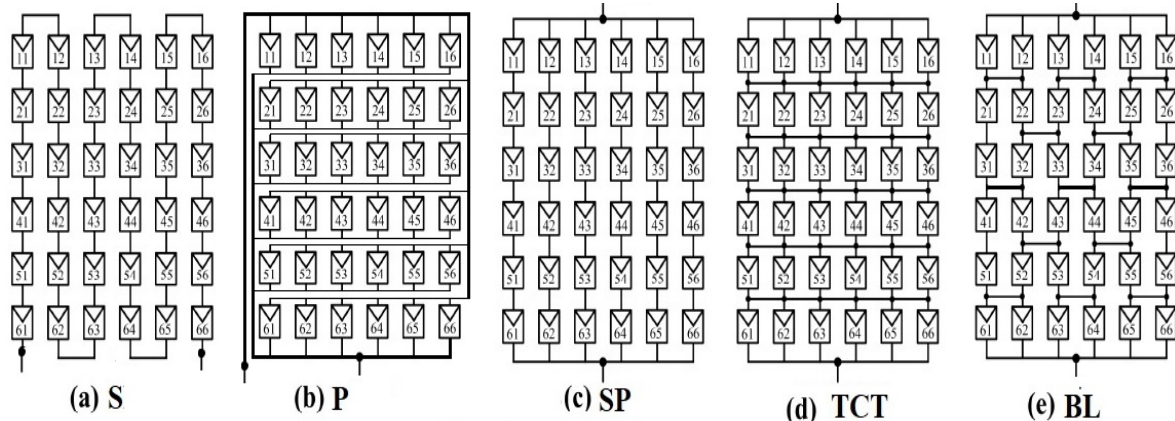


Figure 3. Traditional 6×6 size SPV array configurations

Modeling of TCT Configuration

The TCT (Total Cross Tied) configuration is a series-parallel version in which all rows are cross-linked to the TCT type structure. PV array's lifespan is nearly doubled by the introduction of cross-links to increase the array power. As a result of the connecting links, more loops are created. Because of this, few effects are investigated: voltage limitations in the array are found, and different currents flow throughout the same-string PV panels. In order to locate the global peak (GP) power, it is extremely important to calculate row currents in the TCT form. The current row estimate for a TCT scheme is considered to be a 6×6 PV array.

The output current in a row is the sum of the module current limits. The array currents are calculated for any TCT row by:

$$I_{Rn} = \sum_{n=1}^6 I_m * S_n \quad \text{--- (4)}$$

where I_m is the PV module's maximum current at full irradiance of 1000 W/m² (STC), and $S_n = G_s/G_0$, in which G_s is the solar irradiance at shaded condition, and G_0 is the STC irradiance. Figure 3(d) illustrates the 6×6 TCT array, and the array voltage for six rows is given by the Kirchhoff's Voltage Law (KVL) as:

$$V_a = \sum_{i=1}^6 V_{mi} \quad \text{--- (5)}$$

where V_a is the array voltage and V_{mi} is the voltage of i^{th} row of the PV array. Applying the current law of Kirchhoff to calculate the current at each node in the TCT array and the array current is given as:

$$I_a = \sum_{j=1}^6 (I_{ij} - I_{(i+1)j}) = 0, \quad i = 1,2,3,4,5,6 \quad \text{--- (6)}$$

where i and j are the number of row and column, respectively.

Methodology

The General Rule for Proposed SD-TCT Array Configuration

The proposed SD-TCT array arrangement is applicable for the shading sequence or patterns of any size, *i.e.*, the row and column size could be odd or even number. The rule for configuring a general solar pattern can be defined as:

$$n_{ij}, \text{ Where } \begin{cases} i = \text{No. of rows } (i = 1,2,3,4,5,6) \\ j = \text{No. of Columns } (j = 1,2,3,4,5,6) \end{cases}$$

where n_{ij} is written for the n^{th} element of the i^{th} row and j^{th} column of a shading sequence.

To determine the logic number in a column, the following equations can be considered:

$$j = \begin{cases} j, & \text{if } i = 1 \\ j + (i - 1) \cdot \text{floor}\left(\frac{j_{\max}}{3}\right), & i > 1 \end{cases}$$

$$\text{if } j < j_{\max}, \quad j = j$$

$$\text{else } j = j - j_{\max}$$

If any number is repeated in a column (j), just add 1 to the corresponding column, *i.e.*, $j=j+1$, otherwise take the same number in a column.

Formation of Proposed SD-TCT Configuration

An SD-TCT design aims primarily to dispatch shadows around the array under SC by arranging an $i \times j$ array column location with the numbers 1 to j as shown in Table 1. The proposed logic of numbers is developed for $i =$ odd and even for the column location arrangement of the $i \times j$ PV array. The repeating of the numbers in a specific column (C) and row (R) of a PV sequence is avoided by adding 1 to the previous logic number with the goal of obtaining a unique solution. For any array size, the proposed number logic approach is used, which is used in this paper for 6×6 , 6×5 , and 5×6 arrays.

The proposed design, therefore, reveals its pattern for puzzles and arrangements of the PV array optimized for SD-TCT (Shade dispersion based TCT configuration) arrangement in Figure 4. The 1st number in the box represents a logic number, and the 2nd number denotes the column number. The row and column positions in a 6×6 array are arranging with the numbers 1 to 6 in the suggested arrangement, as present in Figure 4(a). Here, the first-row column location of the array contains a number in an upwards order from 1 to 6. Numbers 1 to 6 are grouped from the second row using the proposed number logic approach, as shown in Table 1.

Table 1. Arrangement of a 6x6 array with proposed shade dispersion number logic approach

Columns Rows	C:1	C:2 (C:1 +1)	C:3 (C:2 +1)	C:4 (C:3 +1)	C:5 (C:4 +1)	C:6 (C:5 +1)
R:1	1	2	3	4	5	6
R:2 (R:1 +2)	3	4	5	6	7-6= 1	8-6= 2
R:3 (R:2 +2)	5	6	7-6= 1	8-6= 2	3	4
R:4 (R:3 +2)	7-6=1 1+1= 2	8-6=2 2+1= 3	3+1= 4	4+1= 5	5+1= 6	6+1=7 7-6= 1
R:5 (R:4 +2)	4	5	6	7-6= 1	8-6= 2	3
R:6 (R:5 +2)	6	7-6= 1	8-6= 2	3	4	5

Table 2. Arrangement of a 6x5 array with proposed shade dispersion number logic approach

Columns Rows	C:1	C:2 (C:1 +1)	C:3 (C:2 +1)	C:4 (C:3 +1)	C:5 (C:4 +1)
R:1	1	2	3	4	5
R:2 (R:1 +2)	3	4	5	6	7-6= 1
R:3 (R:2 +2)	5	6	7-6= 1	8-6= 2	3
R:4 (R:3 +2)	7-6=1 1+1= 2	8-6=2 2+1= 3	3+1= 4	4+1= 5	5+1= 6
R:5 (R:4 +2)	4	5	6	7-6= 1	8-6= 2
R:6 (R:5 +2)	6	7-6= 1	8-6= 2	3	4

Table 3. Arrangement of a 5×6 array with proposed shade dispersion number logic approach

Columns Rows	C:1	C:2 (C:1 +1)	C:3 (C:2 +1)	C:4 (C:3 +1)	C:5 (C:4 +1)	C:6 (C:5 +1)
R:1	1	2	3	4	5	6 6-5= 1
R:2 (R:1 +2)	3	4	5	6 6-5= 1	2	3
R:3 (R:2 +2)	5	6 6-5= 1	2	3	4	5
R:4 (R:3 +2)	7-5=2	3	4	5	6 6-5= 1	2
R:5 (R:4 +2)	4	5	6 6-5= 1	2	3	4

11	22	33	44	55	66
31	42	53	64	15	26
51	62	13	24	35	46
21	32	43	54	65	16
41	52	63	14	25	36
61	12	23	34	45	56

(a) 6x6 SD-TCT

11	22	33	44	55
31	42	53	64	15
51	62	13	24	35
21	32	43	54	65
41	52	63	14	25
61	12	23	34	45

(b) 6x5 SD-TCT

11	22	33	44	55	16
31	42	53	14	25	36
51	12	23	34	45	56
21	32	43	54	15	26
41	52	13	24	35	46

(c) 5x6 SD-TCT

Figure 4. Arrangement of 6×6, 6×5 and 5×6 arrays with proposed number logic approach

Re-arrangement of Array Modules in TCT Configuration

Reconfiguration methods are used to spread the partial shade effect with every conventional configuration. Several literature attempts are made to establish the best scheme for PV systems for all operating conditions in order to find the best configuration [15–16]. TCT is now the most feasible interconnections scheme for achieving efficient and sustainable photovoltaic power generation based on crucial evaluations with TCT, BL, and SP. Some scholarly studies for PV array reconfiguration that adopts TCT interconnect are available in the literature. A smart reconfiguration approach is mandatory to define the new positions in a TCT PV array. A new physical shade dispersion device based on the logic number is thus proposed for this work. The method follows the column wise relocation process in order to rearrange the TCT array, which allows shades with a minimum row current difference to be dispersed. The methodology opted for rearrangement of array modules in TCT with a number logic approach, as described in the previous section. The formation of 6×6, 6×5 and 5×6 array configurations with shade dispersion by logic number approach is illustrated in Figure 5(c), 5(d) and 5(e), respectively.

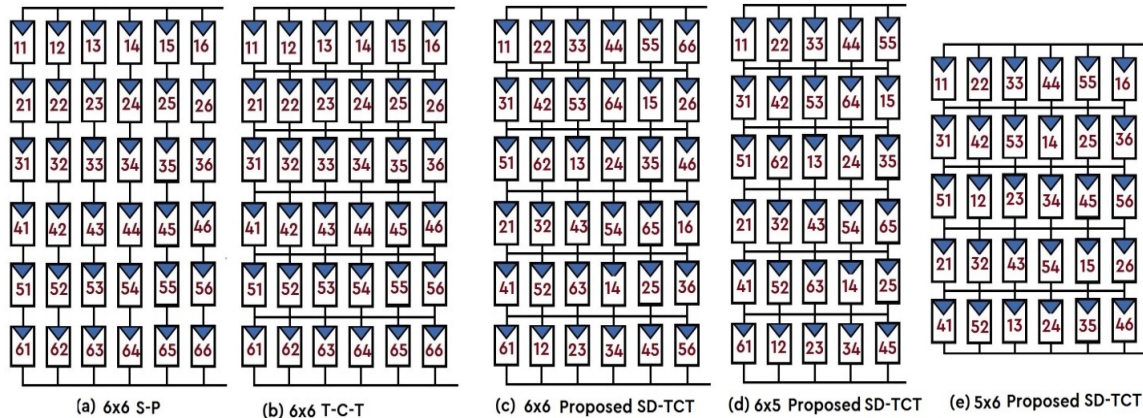


Figure 5. (a)-(b): S-P and TCT, (c)-(e): Re-arrangements of TCT array (SD-TCT)

Physical Relocation of Modules in the Proposed Configuration

The most difficult problem of this procedure was to pick the efficient reconfigurable sequence to spread the shading through the array. The first digit is the logical number in each box in the proposed SD-TCT arrangement, and the 2nd digit indicates the column. This method has the lead of matching the numbers 1 to 6 without repeating them. The purpose of this model system is to share out shadow effects without altering electrical connections by modifying their physical location of PV modules. This means that the panel number 34 is at a third row-fourth column in TCT. But in SD-TCT format, it moves physically into 4th column in the 6th row, as shown in Figure 6(c). Different improvements are made to all PV panels, which increase the current in an entry node and decrease the circumvention of the array modules. This increases the array of power efficiency. Figures 6(b)–6(c) demonstrate the reorganization of array modules by the use of the proposed arrangement without modifying the electrical links to the panels in the shading cases.

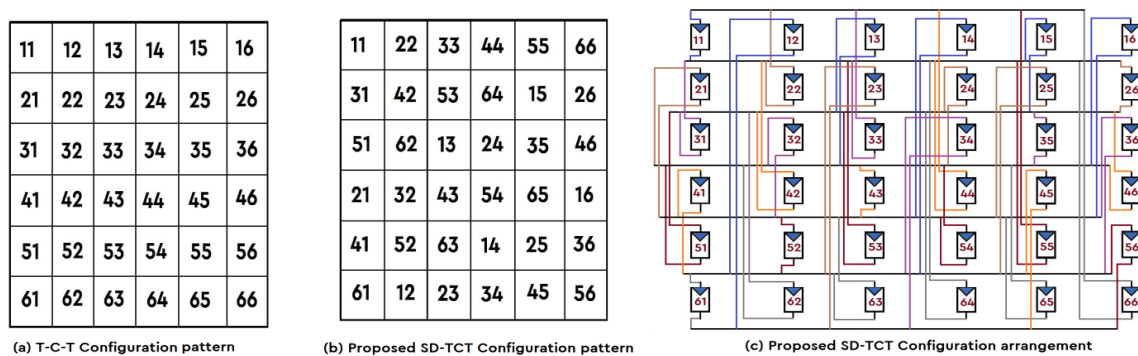


Figure 6. Arrangement of proposed 6×6 SD-TCT array configuration

Analysis of Shading Patterns

Solar PV modules in the array are partly shaded by shadows in surrounding trees, moveable clouds, sand, or dust deposition of the panels. In this paper, shading cases are considered for performance analysis illustrated in Figures 7(a), 9(a), 10(a), and corresponding shade dispersions in SD-TCT configuration are shown in Figures 7(b), 9(b), 10(b), respectively. Each shaded module receives a solar irradiance of 500 W/m^2 , and the maximum irradiance of un-shaded modules is 1000 W/m^2 .

Shading Cases for a 6×6 Array

The shading cases considered for analyzing the shade dispersion in SD-TCT configuration of a 6×6 SPV array is illustrated in Figure 7. Figure 7(a) represents the shading pattern in TCT array connection and Figure 7(b) represents the shade dispersion in SD-TCT arrangement with number logic approach as explained in the previous section. The proposed method disperses the shades on PV module with in a column only. So, in the complete column shading cases, there is no shade dispersion occurs as shown in case-7: single column shading, and case-9: two column shading of a 6×6 array. In non-shading case (*i.e.*, case-U), all 36 modules in a 6×6 PV array receives full irradiance at STC of 1000 W/m².

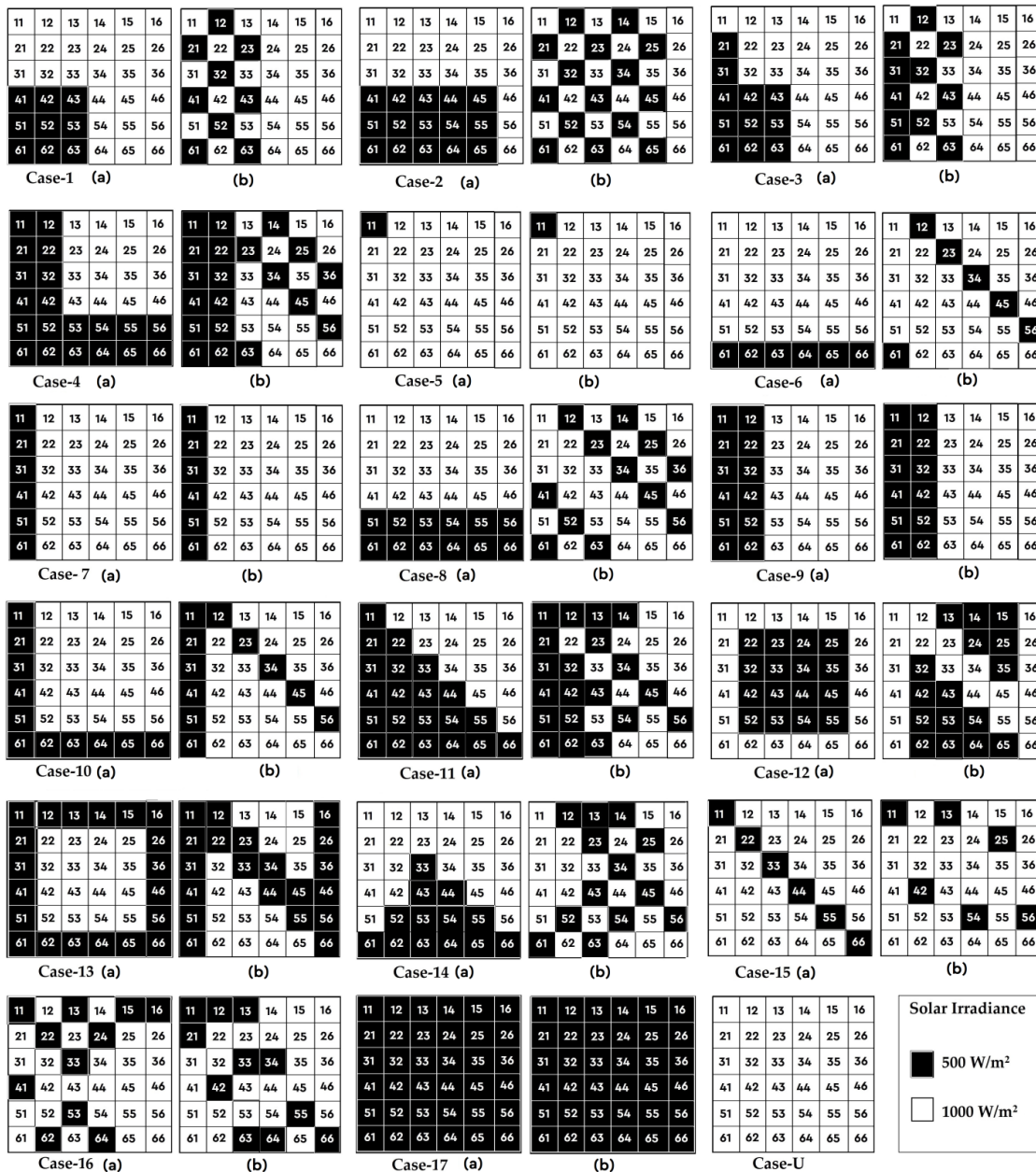


Figure 7. Shade dispersion analysis in a 6×6 array under various shadings:
 (a) TCT (b) SD-TCT configuration

Shade Dispersion in SD-TCT under Shading Case-1 of a 6×6 Array

Any shade extends across the whole array in the proposed SD-TCT system to ensure a maximum current for every node. The shaded row modules are spread over various rows when a shade occurs over a full row, so the current entering every row is almost equal to maximum. Figure 8 explains the dispersion of the shade in the 6th-row partial shading arrangement of TCT and SD-TCT.

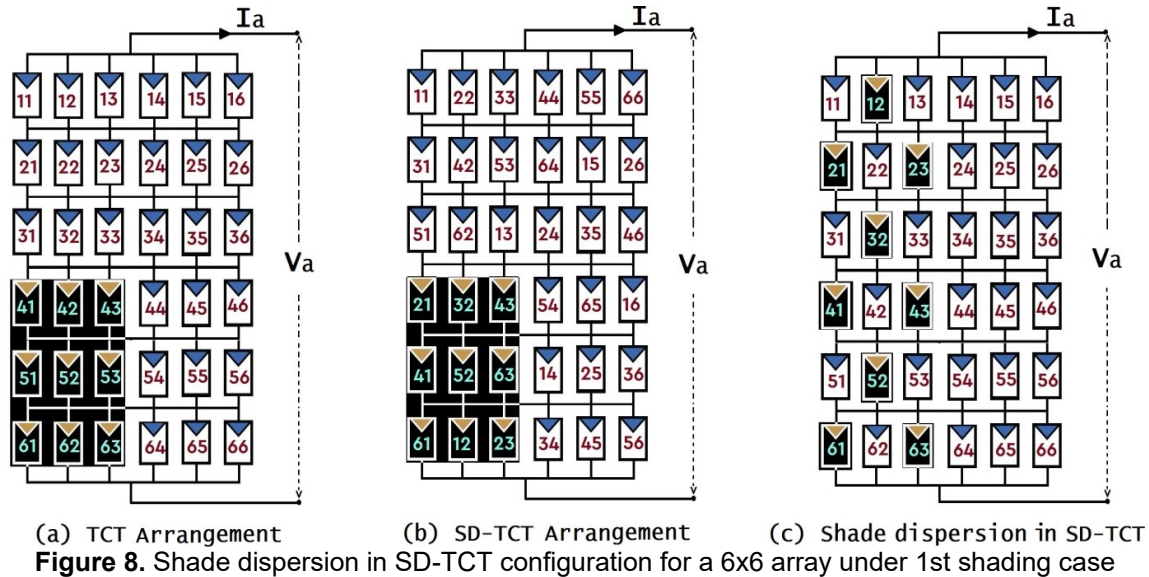


Figure 8. Shade dispersion in SD-TCT configuration for a 6x6 array under 1st shading case

Row Current Estimation

The current in rows assessment shows clear shade in the array arrangements. Moreover, by shifting the row currents, the severity of the shade can be understood clearly. The procedure for row current estimation for a 6×6 TCT under a short narrow shade sequence is given in Figure 8(a) as follows (illustrated in Figure 7: case-1 (a)).

Row Current Estimation in a 6×6 TCT Configuration under Case-1:

The generated current is expressed in equation-(7) in a 6×6 PV array depends on the solar irradiance,

$$I_{Ri} = \sum_{n=1}^6 S_{Mn} I_m = S_{M1} I_m + S_{M2} I_m + S_{M3} I_m + S_{M4} I_m + S_{M5} I_m + S_{M6} I_m \quad \dots \dots \dots (7)$$

where S_{Mn} is the shading factor of the n^{th} PV module in an array.

$$S_{M1} = \left(\frac{G_{M1}}{G_{STC}} \right), S_{M2} = \left(\frac{G_{M2}}{G_{STC}} \right), S_{M3} = \left(\frac{G_{M3}}{G_{STC}} \right), S_{M4} = \left(\frac{G_{M4}}{G_{STC}} \right), S_{M5} = \left(\frac{G_{M5}}{G_{STC}} \right), S_{M6} = \left(\frac{G_{M6}}{G_{STC}} \right) \quad \dots \dots \dots (8)$$

where I_{Ri} is the row current of the i^{th} row. I_m is the PV module's maximum current, G_{SMn} is solar irradiance at the shaded condition, and G_{STC} is irradiance at STC, *i.e.*, 1000 W/m².

The row current of the first, second, third, fourth, fifth, and sixth rows of the TCT arrangements is evaluated as given by:

$$I_{R1} = \left(6 \times \left(\frac{1000}{1000} \right) \times I_m \right) = 6 I_m = I_{R2} = I_{R3}$$

In 1st, 2nd and 3rd rows, all six modules receive full irradiance of 1000 w/m². In 4th, 5th and 6th rows, the irradiance of three modules is 500 W/m², and other three modules have 1000 W/m², as shown in Figure 6(a).

$$I_{R4} = \left(3 \times \left(\frac{1000}{1000}\right) \times I_m\right) + \left(3 \times \left(\frac{500}{1000}\right) \times I_m\right) = (3 \times 1 \times I_m) + (3 \times 0.5 \times I_m) = 4.5 I_m = I_{R5} = I_{R6}$$

Row Current Estimation in a 6×6 Proposed SD-TCT Configuration under Case-1

Compared to the TCT model, a row current assessment was also done by the number logic approach proposed. The row current for the first to the sixth row is set in the following sequence (from Figure 8(c)):

$$1^{\text{st}} \text{ row: } I_{R1} = (1 \times 0.5 \times I_m) + (5 \times 1 \times I_m) = 5.5 I_m$$

$$2^{\text{nd}} \text{ row: } I_{R2} = (2 \times 0.5 \times I_m) + (4 \times 1 \times I_m) = 5 I_m$$

$$3^{\text{rd}} \text{ row: } I_{R3} = (1 \times 0.5 \times I_m) + (5 \times 1 \times I_m) = 5.5 I_m$$

$$4^{\text{th}} \text{ row: } I_{R4} = (2 \times 0.5 \times I_m) + (4 \times 1 \times I_m) = 5 I_m$$

$$5^{\text{th}} \text{ row: } I_{R5} = (1 \times 0.5 \times I_m) + (5 \times 1 \times I_m) = 5.5 I_m$$

$$6^{\text{th}} \text{ row: } I_{R6} = (2 \times 0.5 \times I_m) + (4 \times 1 \times I_m) = 5 I_m$$

Row Current Estimation in a 6×6 Proposed SD-TCT Configuration under Cases-1 to 17:

Similarly by using the equation-(7), the row currents in a 6×6, 6×5 and 5×6 arrays are calculated under proposed 17 different shading cases (illustrated in Figures-7, 9 and 10). The calculated theoretical values of voltage, current and power for a 6×6 array TCT and SD-TCT configuration are tabulated in Table 4. In Table 4, IR is the PV modules row current that is gradually being bypassed.

Table 4. Theoretical calculations of V, I and P for a 6×6 array TCT and SD-TCT configurations

TCT Configuration			SD-TCT Configuration			Highest power: P (×V _m I _m)	Best Configuration
Row maximum currents: I _R (× I _m)	Available Voltage: V (× V _m)	Power: P (×V _m I _m)	Row maximum currents: I _R (× I _m)	Available Voltage: V (× V _m)	Power: P (×V _m I _m)		
Case-U							
I _{R1} = 6	6	36	I _{R1} = 6	6	36	36	TCT/ SD-TCT
I _{R2} = 6	5	30	I _{R2} = 6	5	30		
I _{R3} = 6	4	24	I _{R3} = 6	4	24		
I _{R4} = 6	3	18	I _{R4} = 6	3	18		
I _{R5} = 6	2	12	I _{R5} = 6	2	12		
I _{R6} = 6	1	6	I _{R6} = 6	1	6		
Case-1							
I _{R6} = 4.5	6	27	I _{R6} = 5	6	30	30	SD-TCT
I _{R5} = 4.5	5	22.5	I _{R4} = 5	5	25		
I _{R4} = 4.5	4	18	I _{R2} = 5	4	20		
I _{R3} = 6	3	18	I _{R5} = 5.5	3	16.5		
I _{R2} = 6	2	12	I _{R3} = 5.5	2	11		
I _{R1} = 6	1	6	I _{R1} = 5.5	1	5.5		

Case-2						
$I_{R6}=3.5$	6	21	$I_{R6}=4.5$	6	27	
$I_{R5}=3.5$	5	17.5	$I_{R4}=4.5$	5	22.5	
$I_{R4}=3.5$	4	14	$I_{R2}=4.5$	4	18	27
$I_{R3}=6$	3	18	$I_{R5}=5$	3	15	SD-TCT
$I_{R2}=6$	2	12	$I_{R3}=5$	2	10	
$I_{R1}=6$	1	6	$I_{R1}=5$	1	5	
Case-3						
$I_{R6}=4.5$	6	27	$I_{R6}=5$	6	30	
$I_{R5}=4.5$	5	22.5	$I_{R5}=5$	5	25	
$I_{R4}=4.5$	4	18	$I_{R4}=5$	4	20	30
$I_{R3}=5.5$	3	16.5	$I_{R3}=5$	3	15	SD-TCT
$I_{R2}=5.5$	2	11	$I_{R2}=5$	2	10	
$I_{R1}=6$	1	6	$I_{R1}=5.5$	1	5.5	
Case-4						
$I_{R6}=3$	6	18	$I_{R3}=4$	6	24	
$I_{R5}=3$	5	15	$I_{R2}=4$	5	20	
$I_{R4}=5$	4	20	$I_{R1}=4.5$	4	18	24
$I_{R3}=5$	3	15	$I_{R6}=4.5$	3	13.5	SD-TCT
$I_{R2}=5$	2	10	$I_{R5}=4.5$	2	9	
$I_{R1}=5$	1	5	$I_{R4}=4.5$	1	4.5	
Case-5						
$I_{R1}=5.5$	6	33	$I_{R1}=5.5$	6	33	
$I_{R2}=6$	5	30	$I_{R2}=6$	5	30	
$I_{R3}=6$	4	24	$I_{R3}=6$	4	24	33
$I_{R4}=6$	3	18	$I_{R4}=6$	3	18	TCT/ SD-TCT
$I_{R5}=6$	2	12	$I_{R5}=6$	2	12	
$I_{R6}=6$	1	6	$I_{R6}=6$	1	6	
Case-6						
$I_{R6}=3$	6	18	$I_{R6}=5.5$	6	33	
$I_{R5}=6$	5	30	$I_{R5}=5.5$	5	27.5	
$I_{R4}=6$	4	24	$I_{R4}=5.5$	4	22	33
$I_{R3}=6$	3	18	$I_{R3}=5.5$	3	16.5	SD-TCT
$I_{R2}=6$	2	12	$I_{R2}=5.5$	2	11	
$I_{R1}=6$	1	6	$I_{R1}=5.5$	1	5.5	
Case-7						
$I_{R6}=5.5$	6	33	$I_{R6}=5.5$	6	33	
$I_{R5}=5.5$	5	27.5	$I_{R5}=5.5$	5	27.5	
$I_{R4}=5.5$	4	22	$I_{R4}=5.5$	4	22	33
$I_{R3}=5.5$	3	16.5	$I_{R3}=5.5$	3	16.5	TCT/ SD-TCT
$I_{R2}=5.5$	2	11	$I_{R2}=5.5$	2	11	
$I_{R1}=5.5$	1	5.5	$I_{R1}=5.5$	1	5.5	
Case-8						
$I_{R6}=3$	6	18	$I_{R6}=5$	6	30	
$I_{R5}=3$	5	15	$I_{R5}=5$	5	25	
$I_{R4}=6$	4	24	$I_{R4}=5$	4	20	30
$I_{R3}=6$	3	18	$I_{R3}=5$	3	15	SD-TCT
$I_{R2}=6$	2	12	$I_{R2}=5$	2	10	
$I_{R1}=6$	1	6	$I_{R1}=5$	1	5	
Case-9						
$I_{R6}=5$	6	30	$I_{R6}=5$	6	30	
$I_{R5}=5$	5	25	$I_{R5}=5$	5	25	
$I_{R4}=5$	4	20	$I_{R4}=5$	4	20	30
						TCT/

$I_{R3}=5$	3	15	$I_{R3}=5$	3	15		SD-TCT
$I_{R2}=5$	2	10	$I_{R2}=5$	2	10		
$I_{R1}=5$	1	5	$I_{R1}=5$	1	5		
Case-10							
$I_{R6}=3$	6	18	$I_{R1}=5$	6	30		
$I_{R5}=5.5$	5	27.5	$I_{R2}=5$	5	25		
$I_{R4}=5.5$	4	22	$I_{R3}=5$	4	20	30	SD-TCT
$I_{R3}=5.5$	3	16.5	$I_{R4}=5$	3	15		
$I_{R2}=5.5$	2	11	$I_{R5}=5$	2	10		
$I_{R1}=5.5$	1	5.5	$I_{R6}=5.5$	1	5.5		
Case-11							
$I_{R6}=3$	6	18	$I_{R5}=4$	6	24		
$I_{R5}=3.5$	5	17.5	$I_{R4}=4$	5	20		
$I_{R4}=4$	4	16	$I_{R1}=4$	4	16	24	SD-TCT
$I_{R3}=4.5$	3	13.5	$I_{R6}=4.5$	3	13.5		
$I_{R2}=5$	2	10	$I_{R3}=4.5$	2	9		
$I_{R1}=5.5$	1	5.5	$I_{R2}=5$	1	5		
Case-12							
$I_{R2}=4$	6	24	$I_{R6}=4$	6	24		
$I_{R3}=4$	5	20	$I_{R5}=4.5$	5	22.5		
$I_{R4}=4$	4	16	$I_{R1}=4.5$	4	18	24	TCT/ SD-TCT
$I_{R5}=4$	3	12	$I_{R4}=5$	3	15		
$I_{R6}=6$	2	12	$I_{R3}=5$	2	10		
$I_{R1}=6$	1	6	$I_{R2}=5$	1	2		
Case-13							
$I_{R1}=3$	6	18	$I_{R4}=4$	6	24		
$I_{R6}=3$	5	15	$I_{R3}=4$	5	20		
$I_{R5}=5$	4	20	$I_{R2}=4$	4	16		
$I_{R4}=5$	3	15	$I_{R1}=4.5$	3	13.5	24	SD-TCT
$I_{R3}=5$	2	10	$I_{R5}=4.5$	2	9		
$I_{R2}=5$	1	5	$I_{R6}=5$	1	5		
Case-14							
$I_{R6}=3$	6	18	$I_{R5}=4.5$	6	27		
$I_{R5}=4$	5	20	$I_{R1}=4.5$	5	22.5		
$I_{R4}=5$	4	20	$I_{R2}=5$	4	20	27	SD-TCT
$I_{R3}=5.5$	3	16.5	$I_{R4}=5$	3	15		
$I_{R2}=6$	2	12	$I_{R6}=5$	2	10		
$I_{R1}=6$	1	6	$I_{R3}=5.5$	1	5.5		
Case-15							
$I_{R6}=5.5$	6	33	$I_{R1}=5$	6	30		
$I_{R5}=5.5$	5	27.5	$I_{R5}=5$	5	25		
$I_{R4}=5.5$	4	22	$I_{R4}=5.5$	4	22	33	TCT
$I_{R3}=5.5$	3	16.5	$I_{R2}=5.5$	3	16.5		
$I_{R2}=5.5$	2	11	$I_{R3}=6$	2	12		
$I_{R1}=5.5$	1	5.5	$I_{R6}=6$	1	6		
Case-16							
$I_{R1}=4$	6	24	$I_{R6}=4.5$	6	27		
$I_{R2}=5$	5	25	$I_{R1}=4.5$	5	22.5		
$I_{R6}=5$	4	20	$I_{R3}=5$	4	20		
$I_{R5}=5.5$	3	16.5	$I_{R5}=5.5$	3	16.5	27	SD-TCT
$I_{R4}=5.5$	2	11	$I_{R4}=5.5$	2	11		
$I_{R3}=5.5$	1	5.5	$I_{R2}=5.5$	1	5.5		
Case-17							

$I_{R6}=3$	6	18	$I_{R6}=3$	6	18	18	TCT/ SD-TCT
$I_{R5}=3$	5	15	$I_{R5}=3$	5	15		
$I_{R4}=3$	4	12	$I_{R4}=3$	4	12		
$I_{R3}=3$	3	9	$I_{R3}=3$	3	9		
$I_{R2}=3$	2	6	$I_{R2}=3$	2	6		
$I_{R1}=3$	1	3	$I_{R1}=3$	1	3		

Shading Cases for a 5x6 Array

The shading cases considered for analyzing the shade dispersion in a 5x6 SD-TCT array configuration are illustrated in Figure 9. Figure 9 (a) represents the shading pattern in TCT array connection and 9(b) represents the shade dispersion in SD-TCT arrangement with number logic approach. In non-shading case, *i.e.*, case-U, 30 modules in a 6x5 PV array receive full irradiance at STC of 1000 W/m².

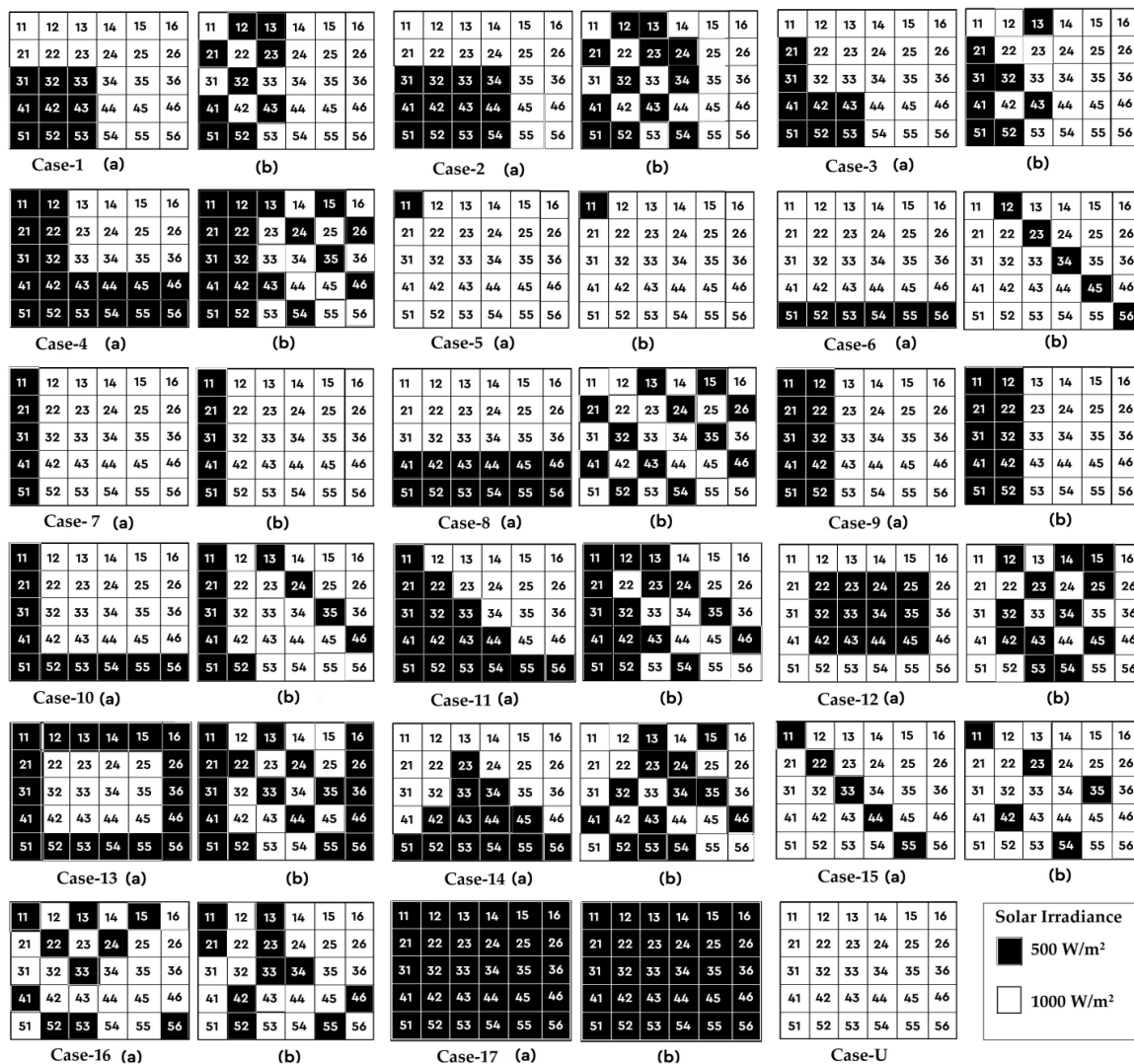


Figure 9. Shade dispersion analysis in a 5x6 array under various shadings:
(a) TCT (b) SD-TCT configuration

Shading Cases for a 6x5 Array

Shading cases for shadow dispersion analysis in a 6x5 SD-TCT configuration are shown in Figure 10. Figure 10(a) represents the shading pattern in TCT array connection,

and 10(b) represents the shade dispersion in SD-TCT arrangement with a number logic approach as explained in the formation of the SD-TCT section. In un-shading case, *i.e.*, case-U, 30 modules in a 6×5 PV array receive full irradiance at STC is 1000 W/m².

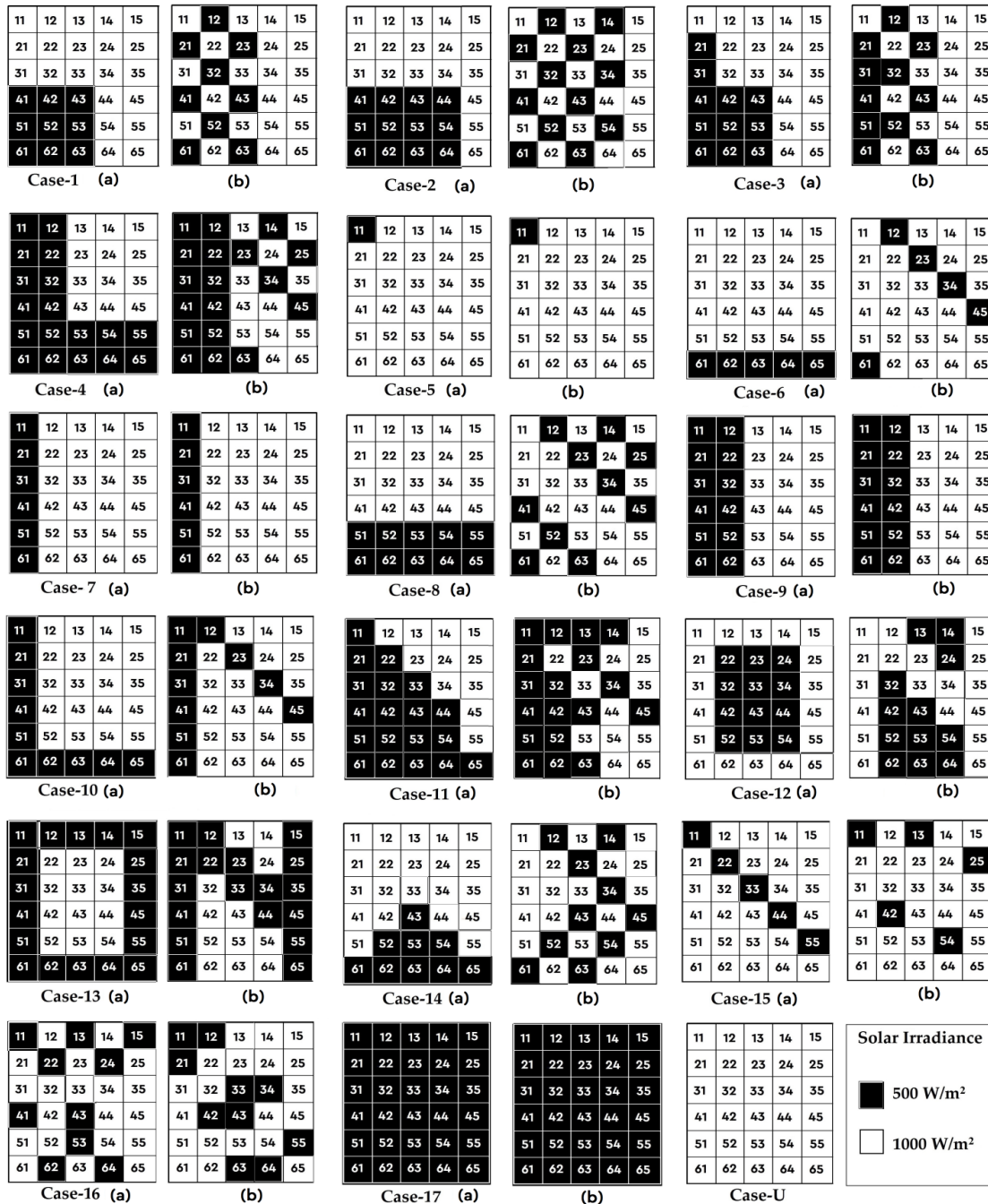


Figure 10. Shade dispersion analysis in a 6x5 array under various shadings: (a) TCT (b) SD-TCT configuration

Suppose considering case-6, PV modules in the sixth row of a 6×5 TCT array are partially shaded with an irradiance of 500 W/m² and other five rows are fully illuminated on sun irradiance as elaborated in Figure-10:case-6(a). The shaded modules in the 6th row are physically moved within a column based on the shade dispersion number logic approach, but electrical wiring is unchanged, as shown in Figure-10:case-6(b). The 6th-row modules in 61 to 66 are shaded in the TCT array and the proposed SD-TCT

arrangement provides shaded modules 61, 12, 23, 34, 45, which are positioned in different rows in a 6×5 PV array and thus shades are spread in an SD-TCT arrangement throughout the PV array. In the same way, shadows are spread in the entire PV array system for other cases.

Results and Discussion

Performance Analysis

To evaluate the performance of 6×6, 6×5 and 5×6 array size SP, TCT and proposed SD-TCT arrangements, three factors including Global Maximum Power Point (GMPP), mismatch losses (ML), % power improvement in SD-TCT under different shading cases are considered in this paper, which are displayed in Figures 7, 9 and 10, respectively. The ML exists between the parameters of the PV module under SC, as the modules obtain different intensities of solar radiation. ML is the distinction between the received peak power in the un-shaded case with an irradiance of 1000W/m² (GMPP_{uni}) and the maximum power under various shadings (GMPP_{SCs}).

$$\text{Mismatch losses}(ML) = GMPP_{uni} - GMPP_{SCs} \quad \text{--- (8)}$$

$$\text{Power improvement in SD - TCT (\%)} = \frac{GMPP_{SD.TCT} - GMPP_{TCT}}{GMPP_{SD.TCT}} \quad \text{--- (9)}$$

- Where, *GMPP* = Global maximum power point in watts(W)
ML = Mismatch Losses in watts(W)
GMPP_{uni} = GMPP at Uniform irradiance of 1000 W/m² in watts(W)
GMPP_{SCs} = GMPP at different shading conditions in watts(W)
GMPP_{SD.TCT} = GMPP of SD-TCT type of array configuration in watts(W)
GMPP_{TCT} = GMPP of TCT type of array configuration in watts(W)
SD - TCT = Shaded Dispersion Based TCT configuration.

Table 5. GMPP and ML of a 6×6 array size configurations

Cases	6×6 array configurations						Minimum ML (W)	Best Configuration
	S-P		T-C-T		SD- TCT			
	GMPP (W)	ML (W)	GMPP (W)	ML (W)	GMPP (W)	ML (W)		
U	9620	0	9620	0	9620	0	0	ALL
1	7384	2236	7714	1906	8309	1311	1311	Proposed
2	5979	3641	6155	3465	7513	2107	2107	Proposed
3	7359	2261	7661	1959	8128	1492	1492	Proposed
4	5208	4412	5433	4187	6815	2805	2805	Proposed
5	8869	751	9352	268	9352	268	268	TCT, Proposed
6	7974	1646	7974	1646	8834	786	786	Proposed
7	8834	786	8834	786	8834	786	786	ALL
8	6328	3292	6328	3292	8049	1571	1571	Proposed
9	8049	1571	8049	1571	8049	1571	1571	ALL
10	7350	2270	7323	2297	8128	1492	1492	Proposed
11	5190	4430	5510	4110	6853	2767	2767	Proposed
12	6617	3003	6778	2842	7057	2563	2563	Proposed
13	5346	4274	5433	4187	6752	2868	2868	Proposed
14	5422	4198	6000	3620	7660	1960	1960	Proposed

15	7974	1646	8834	786	8511	1109	786	TCT
16	6018	3602	7214	2406	7745	1875	1875	Proposed
17	4917	4703	4917	4703	4917	4703	4703	ALL

Table 6. GMPP and ML of a 6×5 array size configurations

Cases	6×5 array configurations						Minimum ML (W)	Best Configuration
	S-P		T-C-T		SD-TCT			
	GMPP (W)	ML (W)	GMPP (W)	ML (W)	GMPP (W)	ML (W)		
U	8017	0	8017	0	8017	0	0	ALL
1	5792	2225	6048	1969	6685	1332	1332	Proposed
2	5094	2923	5263	2754	6445	1572	1572	Proposed
3	5763	2254	6005	2012	6518	1499	1499	Proposed
4	4301	3716	4511	3506	5307	2710	2710	Proposed
5	7307	710	7716	301	7716	301	301	TCT, Proposed
6	6645	1372	6645	1372	7307	710	710	Proposed
7	7231	786	7231	786	7231	786	786	ALL
8	5273	2744	5273	2744	6597	1420	1420	Proposed
9	6445	1572	6445	1572	6445	1572	1572	ALL
10	6022	1995	5994	2023	6597	1420	1420	Proposed
11	4291	3726	4566	3451	5200	2817	2817	Proposed
12	5760	2257	5907	2110	6049	1968	1968	Proposed
13	4302	3715	4511	3506	5228	2789	2789	Proposed
14	4898	3119	5244	2773	6686	1331	1331	Proposed
15	6645	1372	7307	710	6990	1027	710	TCT
16	4864	3153	6190	1827	6597	1420	1420	Proposed
17	4097	3920	4097	3920	4097	3920	3920	ALL

Table 7. GMPP and ML of a 5×6 array size configurations

Cases	5×6 array configurations						Minimum ML (W)	Best Configuration
	S-P		T-C-T		SD-TCT			
	GMPP (W)	ML (W)	GMPP (W)	ML (W)	GMPP (W)	ML (W)		
U	8011	0	8011	0	8011	0	0	ALL
1	6137	1874	6340	1671	6783	1228	1228	Proposed
2	5529	2482	5699	2312	6307	1704	1704	Proposed
3	6135	1876	6459	1552	6871	1140	1140	Proposed
4	4322	3689	4473	3538	5549	2462	2462	Proposed
5	7386	625	7763	248	7763	248	248	TCT, Proposed
6	6365	1646	6365	1646	7096	915	915	Proposed
7	7357	654	7357	654	7357	654	654	ALL
8	4531	3480	4719	3292	6307	1704	1704	Proposed
9	6703	1308	6703	1308	6703	1308	1308	ALL
10	5868	2143	5845	2166	6703	1308	1308	Proposed
11	4348	3663	4651	3360	5754	2257	2257	Proposed
12	5529	2482	5699	2312	6307	1704	1704	Proposed
13	4322	3689	4473	3538	5549	2462	2462	Proposed
14	4450	3561	4733	3278	6210	1801	1801	Proposed
15	6434	1577	7357	654	7357	654	654	TCT, Proposed
16	5377	2634	6515	1496	6703	1308	1308	Proposed

17	4096	3915	4096	3915	4096	3915	3915	ALL
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Table 8. Power improvement in SD-TCT compared to SP and TCT array configurations

Cases	6×6 SPV array			6×5 SPV array			5×6 SPV array		
	SD-TCT Configuration:	% Power improvement in SD-TCT compared to		SD-TCT Configuration:	% Power improvement in SD-TCT compared to		SD-TCT Configuration:	% Power improvement in SD-TCT compared to	
		GMPP (W)	S-P		T-C-T	GMPP (W)		S-P	T-C-T
U	9620	0	0	8017	0	0	8011	0	0
1	8309	11.13	7.16	6685	13.35	9.52	6783	9.52	6.53
2	7513	20.41	18.07	6445	20.96	18.33	6307	12.33	9.64
3	8128	9.46	5.74	6518	11.58	7.87	6871	10.71	5.99
4	6815	23.58	20.27	5307	18.95	14.99	5549	22.11	19.39
5	9352	5.16	0	7716	5.81	0	7763	4.85	0
6	8834	9.73	9.73	7307	9.05	9.05	7096	10.30	10.30
7	8834	0	0	7231	0	0	7357	0	0
8	8049	21.38	21.38	6597	20.06	20.06	6307	28.15	25.17
9	8049	0	0	6445	0	0	6703	0	0
10	8128	9.57	9.90	6597	8.71	9.14	6703	12.45	12.80
11	6853	24.26	19.59	5200	17.48	12.19	5754	24.43	19.16
12	7057	6.23	3.95	6049	4.77	2.34	6307	12.33	9.64
13	6752	20.82	19.53	5228	17.71	13.71	5549	22.11	19.39
14	7660	29.21	21.67	6686	26.74	21.56	6210	28.34	23.78
15	8511	6.30	-3.79	6990	4.93	-4.53	7357	12.54	0
16	7745	22.29	6.85	6597	26.26	6.16	6703	19.78	2.80
17	4917	0	0	4097	0	0	4096	0	0

The findings of the simulation can be inferred:

- Under full irradiance on the PV array (case-U), the global maximum powers are 9620 W, 8017 W, and 8011 W for 6×6, 6×5, and 5×6 array SP, TCT, and proposed SD-TCT configurations, respectively.
- In shading cases-7, 9 and 17: All types of configurations have similar GMPP and minimum ML.
- The TCT and SD-TCT arrangements of power outputs are the same as the shading case-5.
- In 6×6, 6×5, and 5×6 size solar PV arrays, the proposed SD-TCT type of configuration has the highest GMPP's and minimum mismatch losses (ML) in most of the shading cases except in diagonal shape partial shading case-15.
- Compared with the SP and TCT arrangement, the power of SD-TCT has been enhanced, except for the shading cases 5, 7, 9 and 17.

Performance Characteristics of Array Configurations

Figures 11, 12 and 13 show P-V characteristics of 6×6, 6×5, and 5×6 array SD-TCT arrangements under different shading cases. The results find that the performance of a proposed SD-TCT is superior to other types of arrangements.

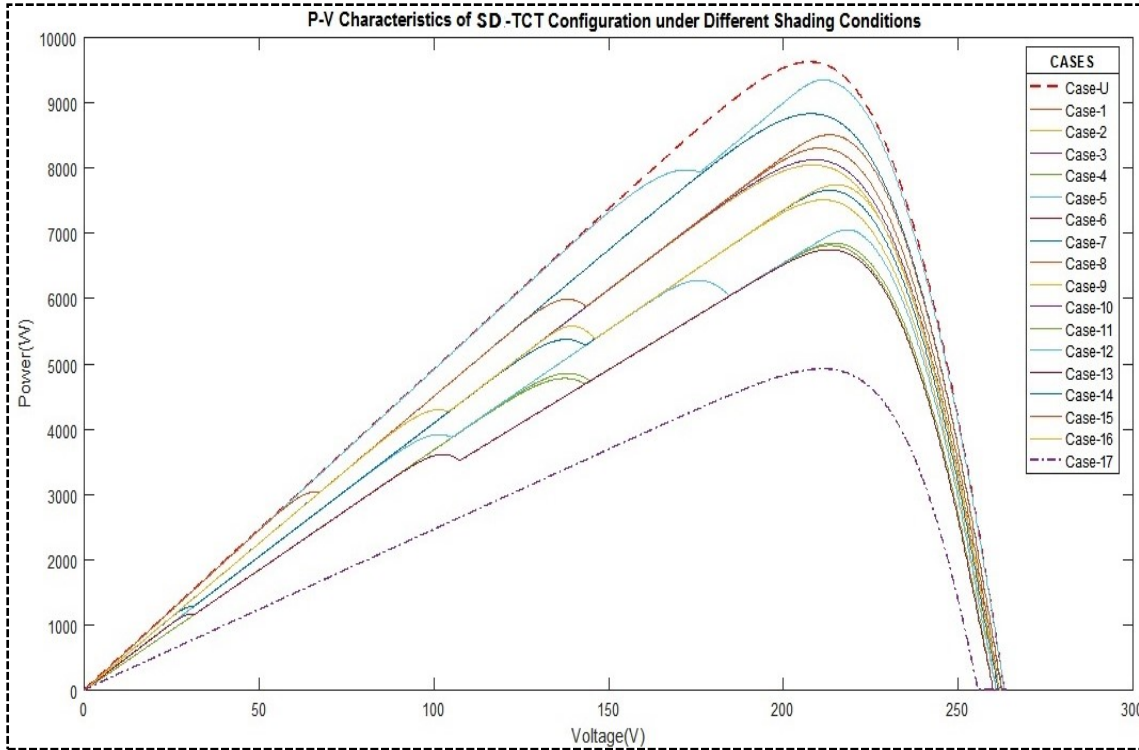


Figure 11. P-V characteristics for 6x6 array size proposed SD-TCT configurations

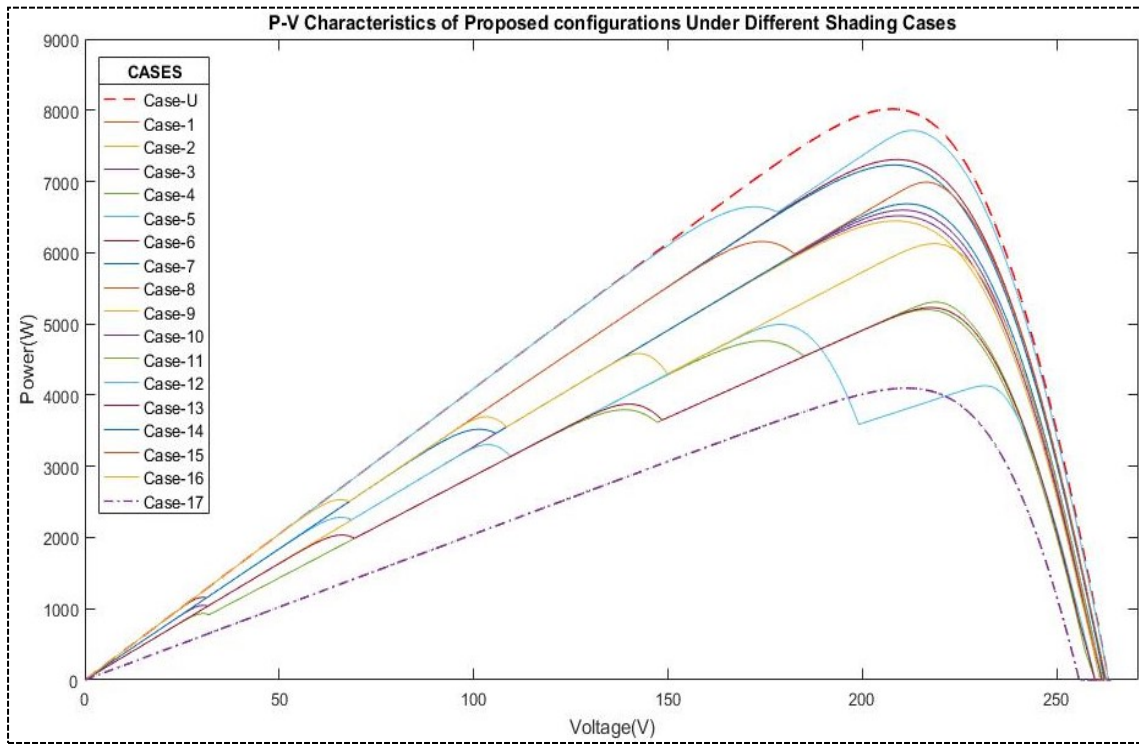


Figure 12. P-V characteristics for 6x5 array size proposed SD-TCT configurations

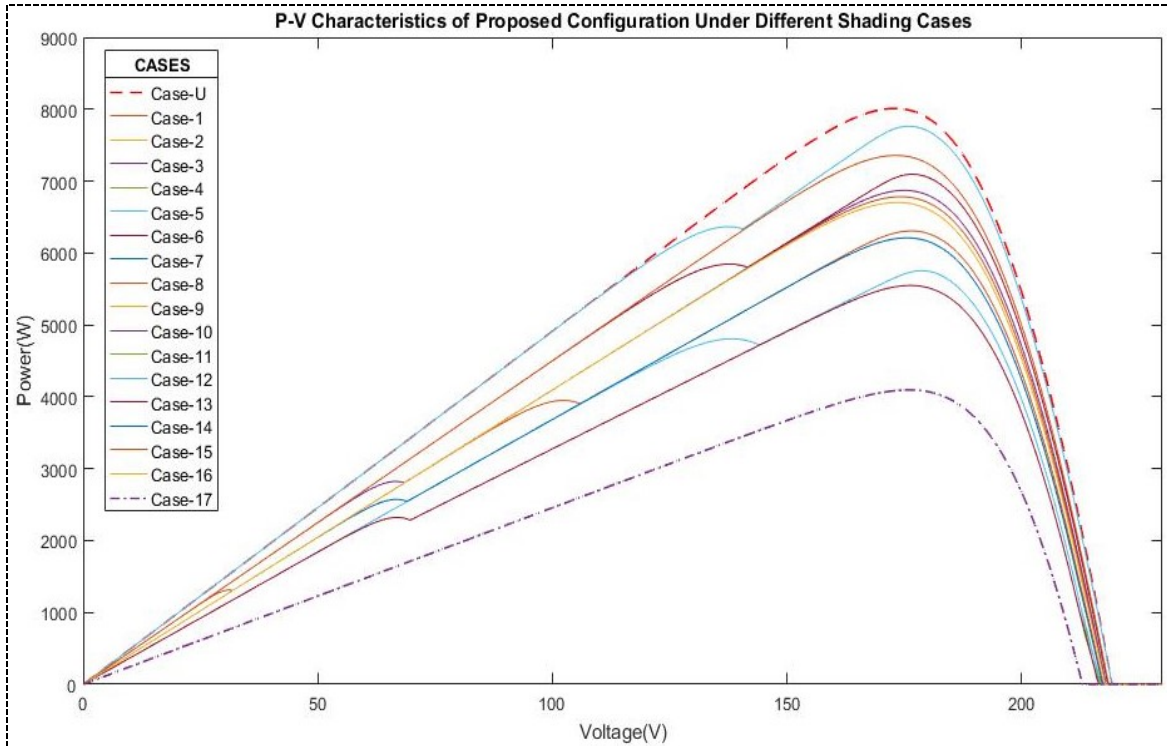


Figure 13. P-V characteristics for 5x6 array size proposed SD-TCT configurations

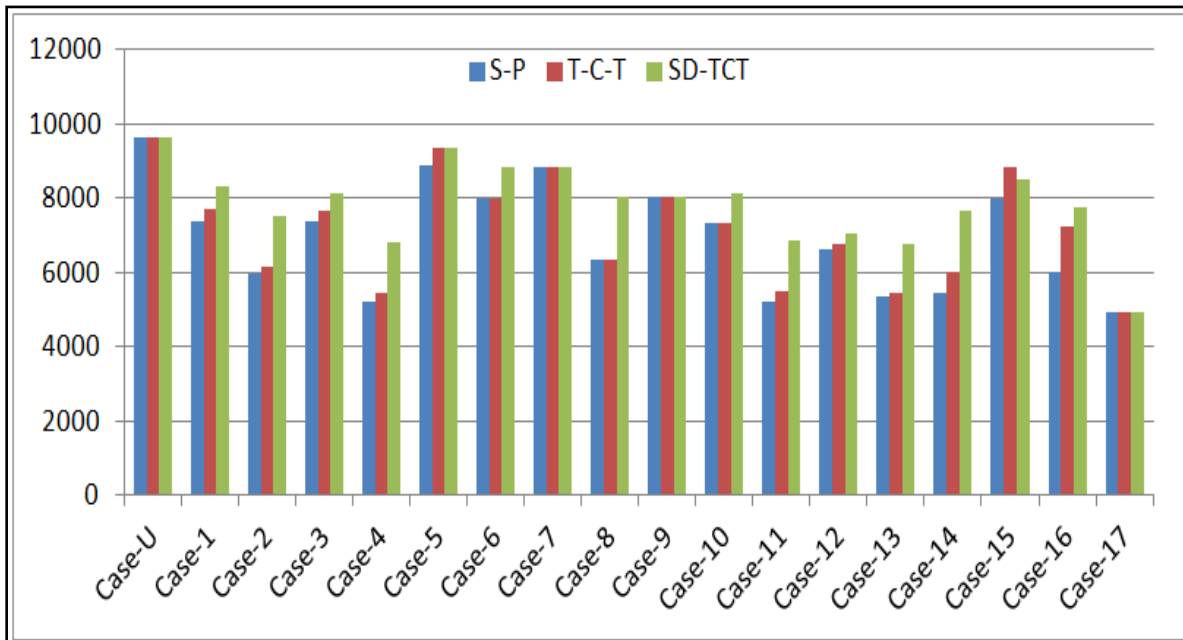


Figure 14. Comparison of GMPP's under different shading cases in 6x6 array size configurations

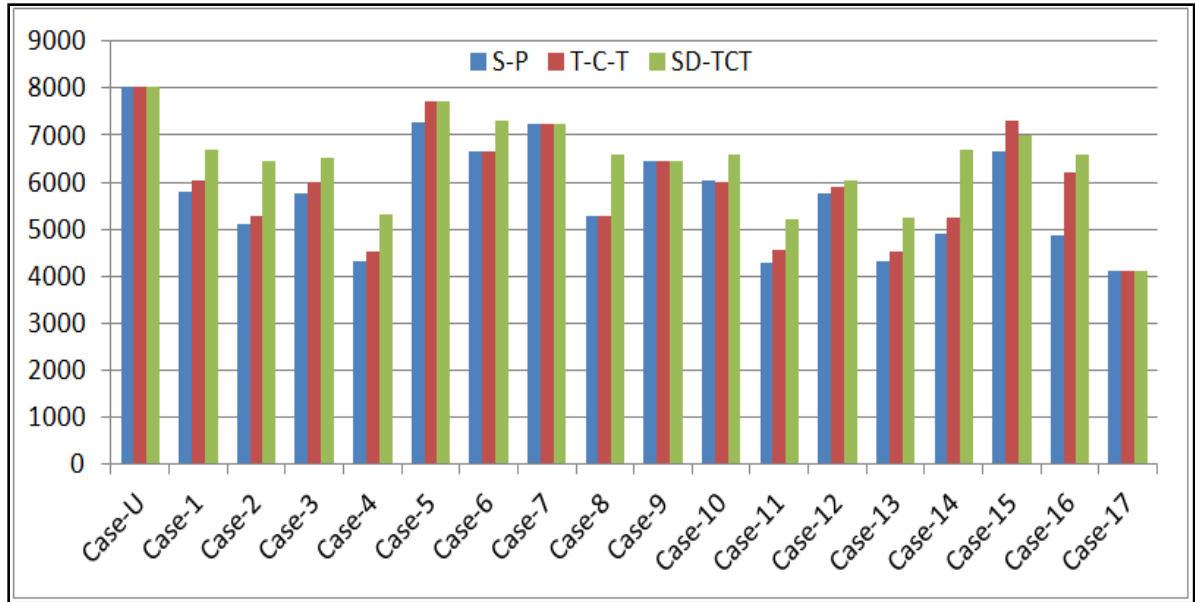


Figure 15. Comparison of GMPP's under different shading cases in 6×5 array size configurations

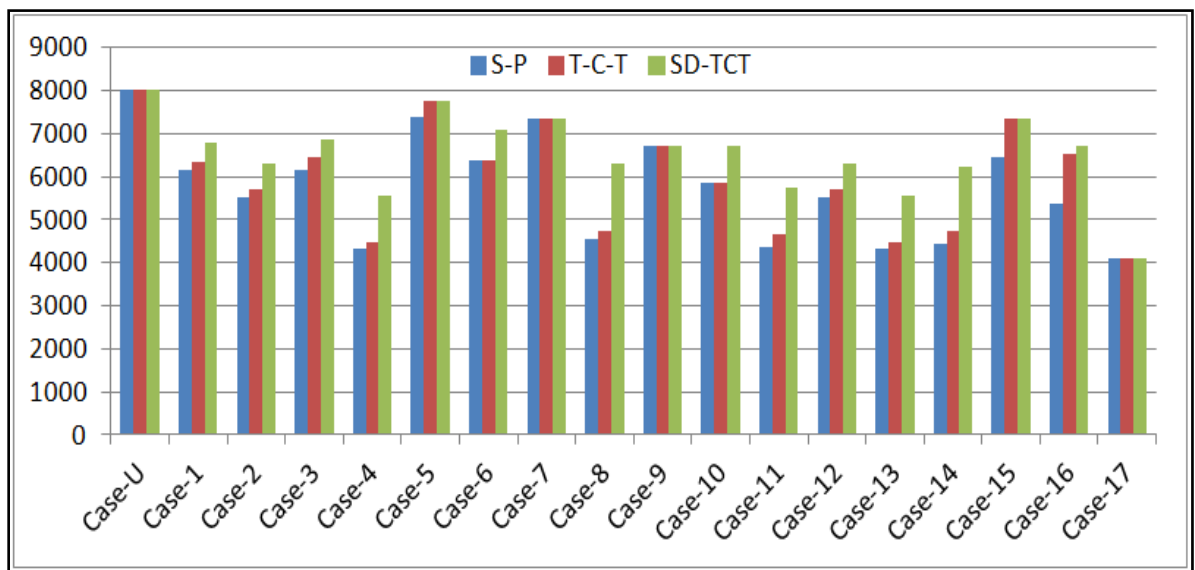


Figure 16. Comparison of GMPP's under different shading cases in 5×6 array size configurations

CONCLUSIONS

In order to optimize the solar PV power in a particular shading cases, this work implements a wide shading effect distribution technique across the array size range of $i \times j$ ($i = j$ and $i \neq j$, where i is row number and j is column number). The physical position of modules for each shading case, without any change in the electric connection, shall only be changed in the proposed method once at the time of the installation. The proposed SD-TCT configuration is cost-effective and easy for implementing a large PV farm in real time, as there are not too many switches and sensors required here. The power provided by SD-TCT is always more than the SP and TCT configuration.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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