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Performance Analysis of PV System Under Partial Shading Conditions

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ABSTRACT:

Solar PV arrays experiences severe reduction in maximum power extraction from the PV power plants when subjected to partial shading conditions (PSC). The main reason for the reduction in maximum power is due to the occurrence of uneven row currents which in turn creates multiple power peaks in output characteristics of PV array. To mitigate this issue array reconfiguration techniques such as physical relocation or electrical relocation are employed. The majority of the physical relocation methods are based on the mathematical puzzles relying on their high shade dispersion capability. But, most of these methods are not suitable to both symmetrical and non-symmetrical PV arrays. In this paper, a new physical relocation method employing skyscraper puzzle is designed and implemented. In this method, physical location of PV modules in TCT array is rearranged without altering their electrical connections. In order to evaluate the performance of proposed skyscraper method, various existing PV array interconnection methods are compared under different shading conditions. The proposed skyscraper method is compared with the Total-Cross-Tied (TCT), Sudoku and Optimal Sudoku methods by using the values acquired from the I-V and P-V characteristics by carryout simulation in MATLAB-Simulink. The results emphasize that, skyscraper method furnish better shade dispersion over the PV array, improves power reduction and reduces mismatch loss when compared with the other methods.

Keywords: Partial shading, Array reconfiguration, Shade dispersion, Mismatch loss.

1. Introduction

The rise in demand for electrical energy day by day across all the sectors including residential, industrial, agricultural, commercial etc., causing the shortage of electrical energy across the globe [1]. Electrical energy is generated by the conventional sources like coal, oil and fossil fuels over the years. The extensive use and exploitation of these natural resources is creating concerns over the environment effects and their depletion and scarcity in few years. Thus, increasing the use of renewable energy sources is inevitable [2].

Among renewable energy sources solar energy has gained substantial attention due to its several advantages such as abundant availability, fuel free, less maintenance and pollution free [3]. The recent advancements in increase in efficiency and decrease in photovoltaic cells cost has made solar energy more preferable [4].

The PV modules power output is affected by several factors such as solar irradiance (G) and ambient temperature (T), variation in series and shunt resistances and partial shading. Partial shading is one of the main reason to diminish the maximum power output and reduce efficiency of the modules [5]. Partial shading arises due to various reasons such as shadows of trees, buildings, poles etc. In large PV systems moving clouds can cause variation in insolation received by the PV modules in the array also leads to partial shading effect. Due to partial shading energy yield of the PV system drastically reduces and it also creates multiple power peaks in the PV characteristics [6], [7]. The multiple power peaks makes it difficult to detect global peak and they can mislead some MPPT algorithms to get trap at local peak points [8], [9]. Different techniques are proposed [10], [11] to track global peak under PSC.

To reduce multiple peaks, reconfiguration method is recommended by various authors in the literature. In reconfiguration method the effect of PSC is minimized by changing the physical location of modules without altering their electrical connections [12]. Several PV arrays such as series-parallel (SP), total-cross-tied (TCT), honey-comb (HC) and bridge-link (BL) are reported in literature. Among all, TCT array performs better to increase maximum power and reduce the effect of PSCs [13]. Changing the PV module interconnection from SP to TCT increases the output power by more than 4% under partially shaded conditions [14]. The authors [15] are proposed a new method to predict the maximum output power production from existing PV systems.

In [16], optimum TCT configuration based on mathematical formulation is developed using branch and bound (BB) algorithm to reduce mismatch losses. In [17], the authors have proposed an optimal reconfiguration method for shifting the location of shaded modules to reduce Mismatch index (MI). A study in [18] based on probability theory shows that the operational life of PV arrays almost doubled with the introduction of cross ties (TCT or BL) in the array. An Electrical Array Reconfiguration (EAR) controller [19] is proposed by the authors, to optimize performance of PV powered volumetric pump. The EAR controller chooses most suitable configuration under different insolation levels and at different operating conditions.

An adaptive reconfiguration scheme [20] is proposed in which a switching matrix connects adaptive part to a fixed part of the array such that less shaded modules of adaptive part are in parallel with more shaded rows of the fixed part. But, to implement this a large number of sensors and switches are required. An electric reconfiguration technique [21] is proposed, in which a switching matrix connected to the modules dynamically changes the connections to maximize current of single string in the event of shading. In [22], the authors have proposed Sudoku puzzle based arrangement for TCT PV array to improve maximum power. The drawbacks of this method is ineffective shading distribution under sub-array matrix and additional wiring requirement. To overcome these drawbacks Optimal Sudoku puzzle based arrangement is proposed in [23].

In this paper, a new 9×9 TCT PV array Skyscraper pattern is proposed, which will increase the maximum power under various shading conditions. The physical locations of the modules are rearranged based on Skyscraper puzzle pattern without altering their electrical connections with in the array. This pattern effectively distributes the shading effect over the array, thereby reducing the occurrence of shading of modules in the same row. The performance of the proposed system is investigated with other reconfiguration schemes namely, total-cross-tied (TCT), Sudoku and Optimal Sudoku. Various performance parameters are evaluated for better assessment of the proposed technique viz., Global Maximum Power Point (GMPP), fill factor (FF), Efficiency (η), Mismatch loss, Power loss and percentage power enhancement.

2. Modelling of 9 × 9 TCT PV Array:

TCT array formation is the new interconnected scheme in PV arrays to reduce partial shadings. To realize TCT, first connect 'n' PV modules in parallel to form the row and many of such rows (m) are then connected in series to form a m × n TCT array. The generalized layout of TCT PV array is shown in fig.1. Modelling is the first and foremost step in analyzing behavior of PV system. The PV array modeling begins with mathematical model of single PV cell. Several solar cell models are reported in literature, of them one diode PV cell model and two diode PV cell model are used extensively. One diode PV cell model is easy to model compared to others. So, in this paper one diode PV cell model is considered for modeling. The one diode PV cell equivalent model is shown in fig.2.

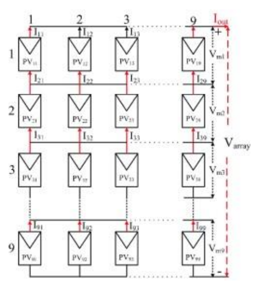


Fig.1: 9 × 9 TCT connected PV array

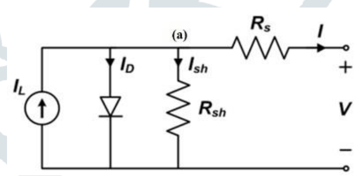


Fig.2: One diode PV cell model

To obtain the current equation apply KCL to node 'a' in Fig.2, I_{cell} can be written as

$$I_{cell} = I_{Lcell} - I_d - I_{sh} \quad (1)$$

Where I_{cell} output current of PV cell, I_{Lcell} is the light generated current of PV cell, I_d is the diode current and I_{sh} is the shunt current current through the shunt resistor. The mathematical expression of single PV cell I-V characteristics can be written as,

$$I_{cell} = I_{Lcell} - I_o\left[\exp\left\{\frac{q(V_m+I_mR_S)}{K_aT}\right\} - 1\right] - (V_m + I_mR_S)/R_{SH} \quad (2)$$

PV module is formed by connecting number of PV cells in series and then enclosed. The PV module's I-V relation is expressed as,

$$I_m = I_L - I_o\left[\exp\left\{\frac{q(V_m+I_mR_s)}{n_sk_aT} - 1\right\}\right] - (V_m + I_mR_S)/R_{SH} \quad (3)$$

By using the above Equation one can find the output current of single PV module. To form the PV array number of such PV modules are first connected in series to form a string and then all strings are connected in parallel. Therefore, The PV module's I-V relation is expressed as,

$$I_a = N_p . I_L - N_P . I_o \exp\left\{\frac{q\left(V_a + \frac{N_S}{N_P} I_a R_S\right)}{N_S knT} - 1\right\} - \left(V_a + \frac{N_S}{N_P} I_a R_S\right) / \left(\frac{N_S}{N_P} R_{SH}\right) \qquad (4)$$

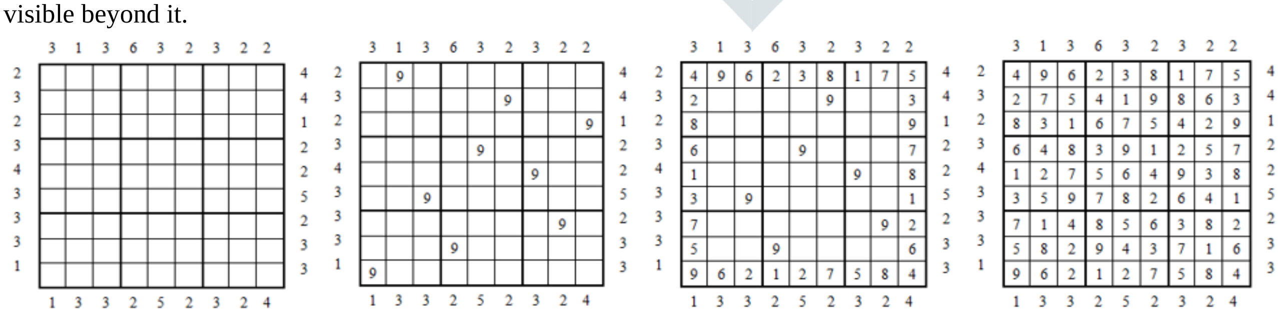
The PV array modeling is carried out by using the above set of equations and the data sheet parameters required to carry out simulation is presented in Table 1.

Table 1: PV module specifications at STC (1000 W/m^2, 25 ºC)

Parameter	Value
Open circuit voltage	22 V
Short circuit current	4.7 A
Nominal voltage	18 V
Nominal current	4.4 A
PV power	80 W

3. SKYSCRAPER PUZZLE:

Skyscraper is one of the Sudoku puzzle methods in which buildings are arranged in puzzle based on their height. A Skyscraper puzzle contains of a N × N square grid with some exterior 'skyscraper' clues. Every square in the grid filled with a skyscraper from 1 to N so that every row and column contains one of each digit as in Sudoku. In every row or column there should be no skyscraper with same height. In skyscraper each digit placed in the grid can be visualized as a building of that many storeys. For instance, digit '9' is a 9 storey building. Each number outside the grid reveals the number of buildings that can be seen from that point if you see in the direction of arrow, looking along the adjacent row or column. Every building blocks all buildings of a lower height from the view while taller buildings are still visible beyond it.



(a) Indicating the clues (b) Locating maximum height (c) Locating immediate height (d) Locating all heights

Fig. 3: Formation of Skyscraper puzzle

The main objective of the proposed skyscraper structure is to apply it on the TCT structured PV array by changing the physical location without altering their electrical connections. The modules are physically relocated according to the skyscraper puzzle as a one time static arrangement for any type of shading. For example, the PV module 92 is connected to the ninth row and second column before the reconfiguration and after reconfiguration the module is shifted to the first row of the array. So the shading effect spread throughout the array. Skyscraper puzzle proposed in this paper is shown in Fig.3. This is a 9×9 skyscraper puzzle consists of 81 square boxes indicating the clues outside the boxes.

4. Shading patterns

For the analysis of performance of PV array for the proposed skyscraper technique, four different shading patterns are used namely Short Wide (SW), Long Wide (LW), Short Narrow (SN) and Long Narrow (LN) are considered. The intensity of a shadow indicates how much power it can filter that shines over module. The intensity of the shadow is called shading factor, the is ranging from 0 (no shadow) to 1 (full shadow). Full shadow means that no irradiance shines over the module and No shadow means all the available irradiance shines over the module.

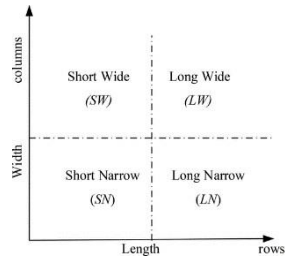


Fig.4: Shading patterns

5. Performance Indices

Performance indices gave the superiority of the reconfiguration techniques under partial shading conditions. Various performance indices like mismatch loss, Power loss, fill factor and percentage power enhancement compared to TCT are considered.

5.1. Mismatch loss

Mismatch loss is the difference between the power at standard test conditions (STC) and power at shaded conditions.

$$Mismatch\ loss = P_{GMPP}\,(unshaded) - P_{GMPP}\,(shaded) \quad (5)$$

5.2. Power loss

Power loss is the ratio of difference between the GMPP at STC and shaded conditions to the GMPP at STC.

$$Power\ loss = \frac{GMPP(STC) - GMPP(shaded)}{GMPP(STC)} \quad (6)$$

5.3. Fill factor (FF)

Fill factor is the ratio of the maximum power generated at shaded condition to the rated capacity of the plant.

$$FF = \frac{V_{mp} \times I_{mp}\ (shaded)}{Voc \times Isc} \quad (7)$$

5.4. Percentage power enhancement compared to TCT

It indicates the power enhancement achieved by the reconfiguration techniques compared to TCT.

$$\%\ Power\ enhancement = \frac{(P_{GMPP}(Sudoku\ /Optimal\ Sudoku\ /Skyscraper\ )) - P_{GMPP}(TCT)}{P_{GMPP}(Sudoku\ /Optimal\ Sudoku\ /Skyscraper\ )} \quad (8)$$

6. Results and Discussions

A 9×9 skyscraper puzzle-based reconfiguration system is proposed in this paper for TCT array to reduce effect of PSC and to increase maximum output power. Four popular shading patterns in literature (SW, LW, SN and LN) are considered to carryout simulation tests. The skyscraper method results are compared with the TCT, Sudoku and Optimal Sudoku methods and are shown in Table.6. Theoretical GMPP calculations are also made to verify the attainment. MATLAB-Simulink is used to carry out the simulations.

6.1. Case 1: Short Wide

In short wide shading pattern, all the modules in the last four rows are partially shaded in the TCT connected PV array. Five distinct groups of insolation levels are considered. The group1 receives insolation of 900 W/m^2 while group 2, group, group4 and group5 receives insolation of 800 W/m^2, 500 W/m^2, 400 W/m^2 and 200 W/m^2 respectively. The shade dispersion achieved by proposed skyscraper method is shown in fig. 5 along with the TCT, Sudoku and Optimal Sudoku shade dispersions.

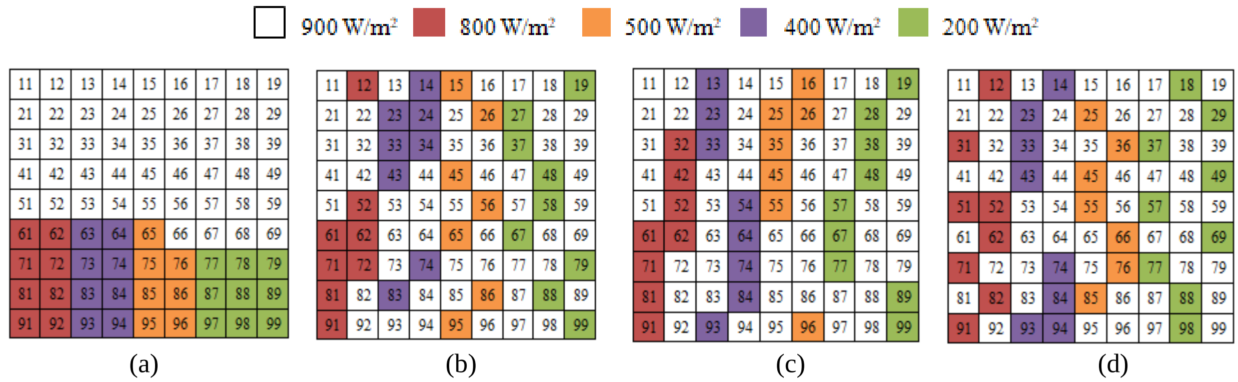


Fig. 5: Shading dispersion in (a) TCT, (b) Sudoku, (c) Optimal Sudoku, (d) Skyscraper for Case 1.

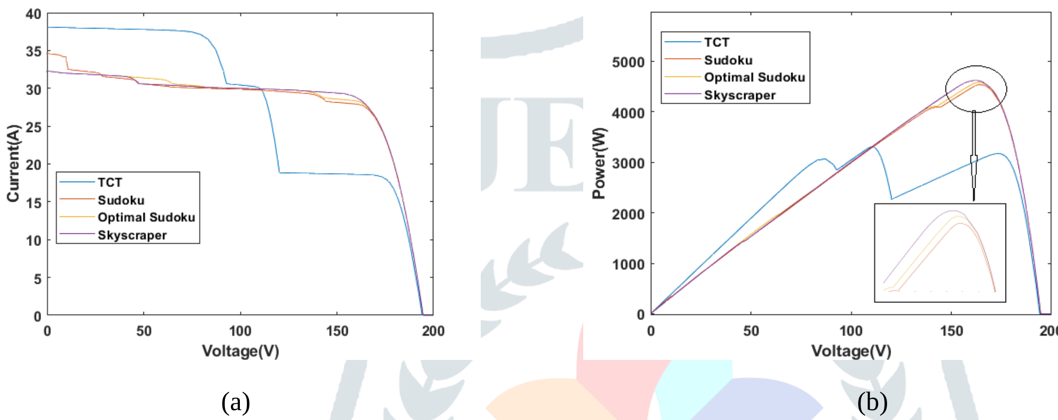


Fig. 6: (a) I-V characteristics and (b) P-V characteristics for Case 1.

Table 2: Location of GMPP for Case 1.

TCT				Sudoku				Optimal Sudoku				Skyscraper			
Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)
7	$4\,I_m$	$9\,V_m$	$36\,V_mI_m$	2	$6\,I_m$	$9\,V_m$	$36\,V_mI_m$	2	$6.1\,I_m$	$9\,V_m$	$54.9\,V_mI_m$	9	$6.3\,I_m$	$9\,V_m$	$56.7\,V_mI_m$
8	$4\,I_m$	-	-	1	$6.4\,I_m$	$8\,V_m$	$51.2\,V_mI_m$	3	$6.4\,I_m$	$8\,V_m$	$51.2\,V_mI_m$	3	$6.4\,I_m$	$8\,V_m$	$51.2\,V_mI_m$
9	$4\,I_m$	-	-	3	$6.4\,I_m$	-	-	5	$6.4\,I_m$	-	-	7	$6.4\,I_m$	-	-
6	$6.5\,I_m$	$6\,V_m$	$39\,V_mI_m$	8	$6.4\,I_m$	-	-	9	$6.4\,I_m$	-	-	8	$6.4\,I_m$	-	-
1	$8.1\,I_m$	$5\,V_m$	$40.5\,V_mI_m$	4	$6.5\,I_m$	$5\,V_m$	$32.5\,V_mI_m$	1	$6.5\,I_m$	$5\,V_m$	$32.5\,V_mI_m$	2	$6.5\,I_m$	$5\,V_m$	$32.5\,V_mI_m$
2	$8.1\,I_m$	-	-	7	$6.7\,I_m$	$4\,V_m$	$26.8\,V_mI_m$	6	$6.7\,I_m$	$4\,V_m$	$26.8\,V_mI_m$	4	$6.5\,I_m$	-	-
3	$8.1\,I_m$	-	-	6	$6.8\,I_m$	$3\,V_m$	$20.4\,V_mI_m$	4	$6.8\,I_m$	$3\,V_m$	$20.4\,V_mI_m$	1	$6.8\,I_m$	$3\,V_m$	$20.4\,V_mI_m$
4	$8.1\,I_m$	-	-	5	$6.9\,I_m$	$2\,V_m$	$13.8\,V_mI_m$	7	$6.8\,I_m$	-	-	5	$6.8\,I_m$	-	-
5	$8.1\,I_m$	-	-	9	$6.9\,I_m$	-	-	8	$6.8\,I_m$	-	-	6	$6.9\,I_m$	V_m	$6.9\,V_mI_m$

6.2. Case 2: Long Wide

In Long wide shading pattern, all the modules in the last three rows and last three columns are partially shaded in the TCT connected PV array with different shading levels as shown in fig. Five different insolation levels are considered, group1 receives insolation of 900 W/m^2 while group 2, group 3, group 4 and group5 receives insolation of 700 W/m^2, 500 W/m^2, 400 W/m^2 and 200 W/m^2 respectively. The shade dispersion achieved by TCT, Sudoku, Optimal Sudoku and skyscraper methods are shown in fig. 7.

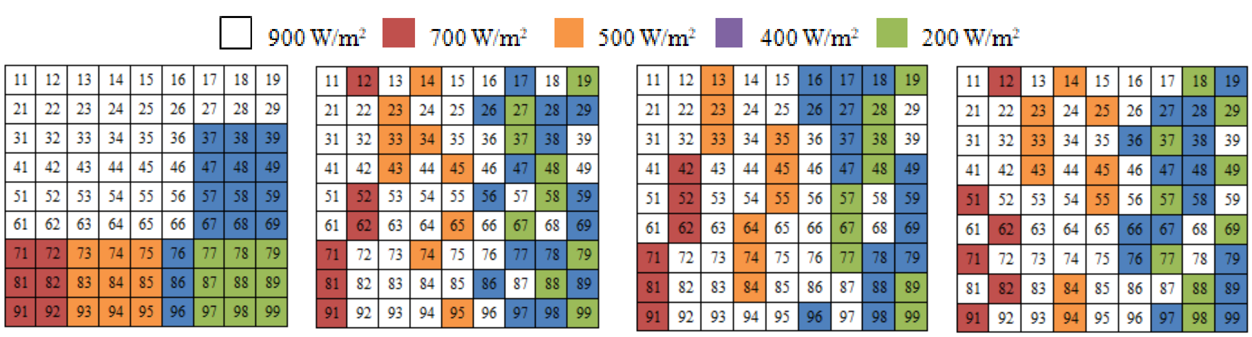
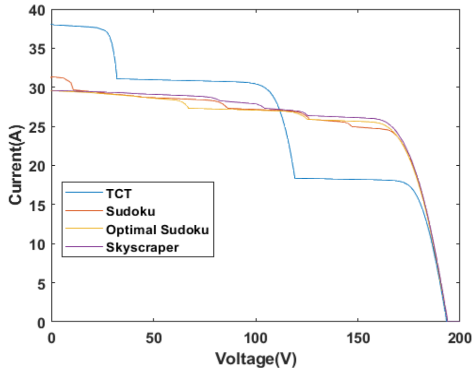
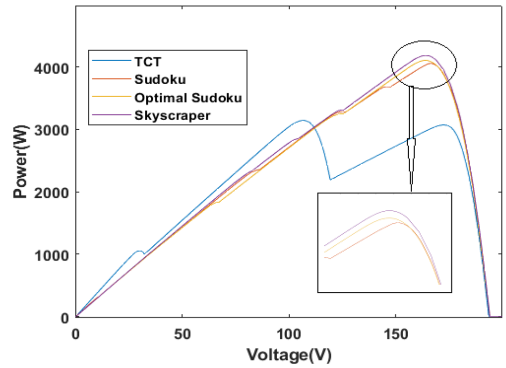


Fig.7: Shading dispersion in (a) TCT, (b) Sudoku, (c) Optimal Sudoku, (d) Skyscraper for Case 2.



(a)



(b)

Fig. 8: (a) I-V characteristics and (b) P-V characteristics for Case 2.

Table 3: GMPP Location for Case 2.

TCT				Sudoku				Optimal Sudoku				Skyscraper			
Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)
7	3.9 I_m	9 V_m	36 V_mI_m	2	5.5 I_m	9 V_m	49.5 V_mI_m	1	5.5 I_m	9 V_m	49.5 V_mI_m	2	5.6 I_m	9 V_m	50.4 V_mI_m
8	3.9 I_m	-	-	7	5.8 I_m	8 V_m	46.4 V_mI_m	4	5.8 I_m	8 V_m	46.4 V_mI_m	4	5.6 I_m	-	-
9	3.9 I_m	-	-	9	5.8 I_m	-	-	7	5.8 I_m	-	-	9	5.8 I_m	7 V_m	40.6 V_mI_m
3	6.6 I_m	6 V_m	39.6 V_mI_m	3	6.1 I_m	6 V_m	36.6 V_mI_m	2	6 I_m	6 V_m	36 V_mI_m	3	6 I_m	6 V_m	36 V_mI_m
4	6.6 I_m	5 V_m	33 V_mI_m	4	6.1 I_m	-	-	3	6.1 I_m	5 V_m	30.5 V_mI_m	6	6.2 I_m	5 V_m	31 V_mI_m
5	6.6 I_m	-	-	5	6.2 I_m	4 V_m	24.8 V_mI_m	9	6.2 I_m	4 V_m	24.8 V_mI_m	7	6.2 I_m	-	-
6	6.6 I_m	-	-	8	6.2 I_m	-	-	5	6.3 I_m	3 V_m	18.9 V_mI_m	1	6.3 I_m	3 V_m	18.9 V_mI_m
1	8.1 I_m	2 V_m	16.2 V_mI_m	1	6.3 I_m	2 V_m	12.6 V_mI_m	6	6.3 I_m	-	-	5	6.3 I_m	-	-
2	8.1 I_m	-	-	6	6.3 I_m	-	-	8	6.3 I_m	-	-	8	6.3 I_m	-	-

6.3. Case 3: Short Narrow

In short narrow shading pattern, three distinct groups of insolation levels namely 900 W/m^2, 600 W/m^2 and 400 W/m^2 are projected on to the TCT PV array. The same shading pattern and insolation levels are applied to the Sudoku, Optimal Sudoku and Skyscraper configurations.

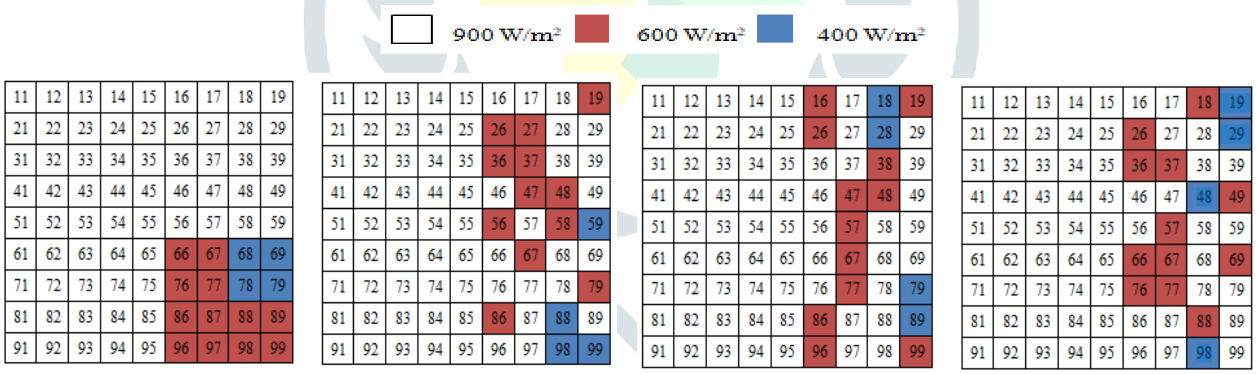
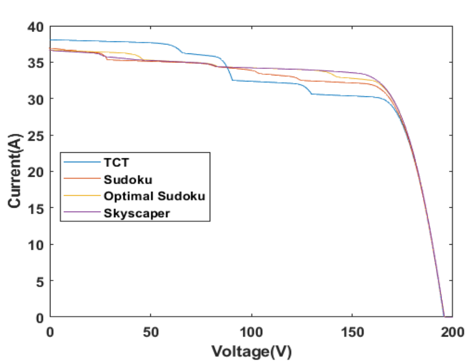
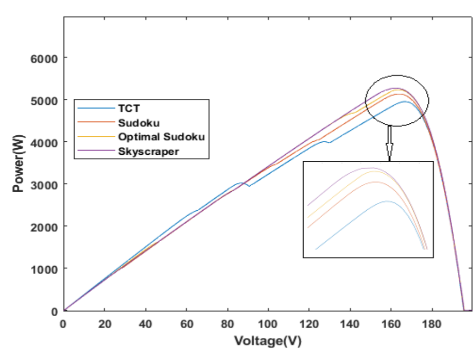


Fig. 9: Shading dispersion in (a) TCT, (b) Sudoku, (c) Optimal Sudoku, (d) Skyscraper for Case 3.



(a)



(b)

Fig. 10: I-V characteristics and (b) P-V characteristics for Case 3.

Table 4: Location of GMPP for Case 3.

TCT				Sudoku				Optimal Sudoku				Skyscraper			
Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)
6	$6.5 I_m$	$9 V_m$	$36 V_mI_m$	5	$7 I_m$	$9 V_m$	$63 V_mI_m$	1	$7 I_m$	$9 V_m$	$63 V_mI_m$	6	$7.2 I_m$	$9 V_m$	$64.8 V_mI_m$
7	$6.5 I_m$	-	-	9	$7.1 I_m$	$8 V_m$	$56.8 V_mI_m$	2	$7.3 I_m$	$8 V_m$	$58.4 V_mI_m$	1	$7.3 I_m$	$8 V_m$	$58.4 V_mI_m$
8	$6.9 I_m$	$7 V_m$	$48.3 V_mI_m$	8	$7.3 I_m$	$7 V_m$	$51.1 V_mI_m$	7	$7.3 I_m$	-	-	2	$7.3 I_m$	-	-
9	$6.9 I_m$	$6 V_m$	$41.4 V_mI_m$	2	$7.5 I_m$	$6 V_m$	$45 V_mI_m$	8	$7.3 I_m$	-	-	4	$7.3 I_m$	-	-
1	$8.1 I_m$	$5 V_m$	$40.5 V_mI_m$	3	$7.5 I_m$	-	-	4	$7.5 I_m$	$5 V_m$	$37.5 V_mI_m$	3	$7.5 I_m$	$5 V_m$	$37.5 V_mI_m$
2	$8.1 I_m$	-	-	4	$7.5 I_m$	-	-	9	$7.5 I_m$	-	-	7	$7.5 I_m$	-	-
3	$8.1 I_m$	-	-	1	$7.8 I_m$	$3 V_m$	$23.4 V_mI_m$	3	$7.8 I_m$	$3 V_m$	$23.4 V_mI_m$	9	$7.6 I_m$	$3 V_m$	$22.8 V_mI_m$
4	$8.1 I_m$	-	-	6	$7.8 I_m$	$2 V_m$	-	5	$7.8 I_m$	-	-	5	$7.8 I_m$	$2 V_m$	$15.6 V_mI_m$
5	$8.1 I_m$	-	-	7	$7.8 I_m$	-	-	6	$7.8 I_m$	-	-	8	$7.8 I_m$	-	-

6.4. Case 4: Long Narrow

In long narrow shading pattern, four distinct groups of insolation levels namely 900 W/m^2, 700 W/m^2, 500 W/m^2 and 300 W/m^2 are applied on the TCT PV array. The shade dispersion achieved by the Sudoku, Optimal Sudoku and Skyscraper configurations for this shading pattern is shown in fig. 11.

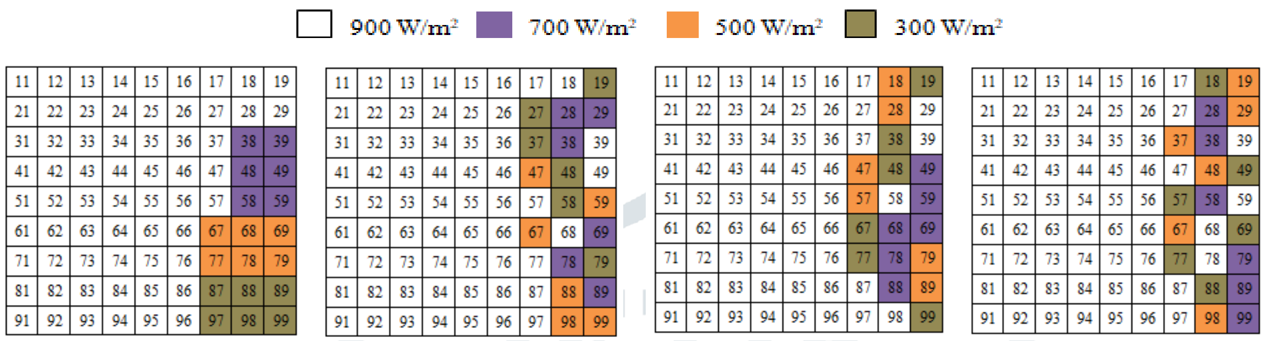


Fig.11: Shading dispersion in (a) TCT, (b) Sudoku, (c) Optimal Sudoku, (d) Skyscraper for Case 4.

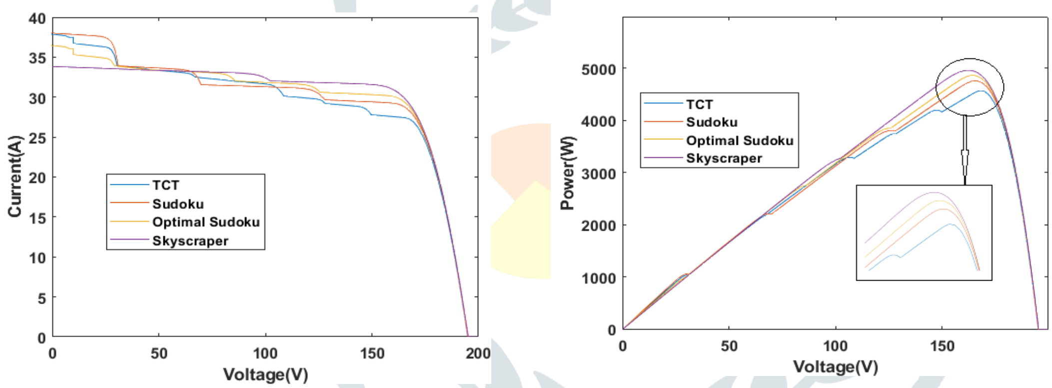


Fig.12: I-V characteristics and (b) P-V characteristics for Case 4.

Table 5: Theoritical Calculations for Case 4

TCT				Sudoku				Optimal Sudoku				Skyscraper			
Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)	Row Bypassed	Current(I_a)	Voltage(V_a)	Power(W)
6	$6.3 I_m$	$9 V_m$	$56.7 V_mI_m$	2	$6.4 I_m$	$9 V_m$	$57.6 V_mI_m$	6	$6.4 I_m$	$9 V_m$	$57.6 V_mI_m$	2	$6.8 I_m$	$9 V_m$	$64.8 V_mI_m$
7	$6.3 I_m$	-	-	6	$6.7 I_m$	$8 V_m$	$53.6 V_mI_m$	4	$6.5 I_m$	$8 V_m$	$52 V_mI_m$	3	$6.8 I_m$	-	-
3	$6.7 I_m$	$7 V_m$	$46.9 V_mI_m$	8	$6.8 I_m$	$7 V_m$	$47.6 V_mI_m$	7	$6.5 I_m$	-	-	9	$6.8 I_m$	-	-
4	$6.7 I_m$	-	-	9	$6.9 I_m$	$6 V_m$	$41.4 V_mI_m$	5	$6.7 I_m$	$6 V_m$	$40.2 V_mI_m$	5	$7.1 I_m$	$6 V_m$	$42.6 V_mI_m$
5	$6.7 I_m$	-	-	3	$7.1 I_m$	$5 V_m$	$35.5 V_mI_m$	8	$6.8 I_m$	$5 V_m$	$34 V_mI_m$	7	$7.1 I_m$	-	-
8	$7.2 I_m$	$4 V_m$	$28.8 V_mI_m$	7	$7.1 I_m$	-	-	1	$7.2 I_m$	$4 V_m$	$28.8 V_mI_m$	8	$7.1 I_m$	-	-
9	$7.2 I_m$	-	-	4	$7.2 I_m$	$3 V_m$	$21.6 V_mI_m$	2	$7.5 I_m$	$3 V_m$	$22.5 V_mI_m$	1	$7.2 I_m$	$3 V_m$	$22.8 V_mI_m$
1	$8.1 I_m$	$2 V_m$	$16.2 V_mI_m$	5	$7.2 I_m$	-	-	3	$7.8 I_m$	$2 V_m$	$15.6 V_mI_m$	4	$7.2 I_m$	-	-
2	$8.1 I_m$	-	-	1	$7.8 I_m$	V_m	$7.8 V_mI_m$	9	$7.8 I_m$	-	-	6	$7.2 I_m$	-	-

The performance parameters Mismatch loss, Power loss, Fill factor, % power enhancement compared to TCT are calculated for TCT, Sudoku, Optimal Sudoku, Skyscraper under SW, SN, LW, LN shading patterns using Equations (5) – (8) and are tabulated in Table 6.

Table 6: Performance parameters comparison for all the shading patterns

Shading Pattern	Configuration	GMPP (W)	Mismatch loss (W)	Power loss (%)	Fill factor	% power enhancement compared to TCT
Short Wide	TCT	3304	3176	49.01	0.39448	-
	Sudoku	4532	1948	30.06	0.54110	27.09
	Optimal Sudoku	4577	1903	29.36	0.54648	27.81
	Skyscraper	4614	1866	28.79	0.55089	28.39
Short Narrow	TCT	3143	3337	51.49	0.37526	-
	Sudoku	4054	2426	37.43	0.48403	22.47
	Optimal Sudoku	4103	2377	36.68	0.48988	23.39
	Skyscraper	4182	2298	35.46	0.49908	24.85
Long Wide	TCT	4957	1523	23.50	0.59185	-
	Sudoku	5139	1341	20.69	0.61358	3.54
	Optimal Sudoku	5240	1240	19.13	0.62564	5.40
	Skyscraper	5272	1208	18.64	0.62946	5.97
Long Narrow	TCT	4570	1910	29.47	0.54564	-
	Sudoku	4757	1723	26.58	0.56797	3.93
	Optimal Sudoku	4860	1620	25.00	0.58027	5.96
	Skyscraper	4959	1521	23.47	0.59209	7.84

The above Table shows that the generated power output is higher for the skyscraper puzzle configuration compared to TCT, Sudoku and Optimal Sudoku configurations. Also, the performance indices shows that the skyscraper method is superior to other reconfiguration methods. Thus, by arranging the PV modules according to the skyscraper puzzle, the power produced by the PV array increases.

Conclusion

This paper proposes a novel 9×9 skyscraper interconnection scheme as a one time arrangement, to increase the power generation of the TCT PV array under different partial shading conditions. In this, the modules are physically relocated according to the skyscraper puzzle pattern without altering their electrical connections. The skyscraper puzzle pattern distribute the shading effects over the entire array and restricts the predominant shading of any one row, thus increases the generated output power. From the performance evaluation of the PV system under different shading conditions, it can be concluded that by positioning the modules in skyscraper pattern global maximum power output and performance under partial shading conditions can be improved.

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