

Modeling and Analysis of PV Configurations to Extract Maximum Power Under Partial Shading Conditions

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Abstract—Photovoltaics (PV) are widely used as renewable energy sources for standalone and grid connected PV systems. But these PV systems face major reduction in output power and efficiency due to Partial Shading Conditions (PSCs). This research paper focuses on the different choices of optimum PV Configuration under a given shading pattern to extract maximum power by mitigating mismatching loss. Various PV configurations, such as Series (S), Series Parallel (SP), Total Cross Tied (TCT), Bridge Linked (BL), Honey Comb (HC) and Alternate Total Cross Tied – Bridge Linked (A-TCT-BL) are modeled and analyzed under PSCs. Nine shading patterns, such as center, diagonal, corner, L-shaped, short and narrow, short and wide, long and narrow, long and wide and random, are considered to study the behavior of a 6×6 array form of a PV Configuration. Their performances are compared based on open circuit voltage, short circuit current, global maximum power point (GMPP), maximum voltage, maximum current, shading loss, fill factor, mismatching loss and efficiency. A novel Hybrid Configuration called A-TCT-BL PV Configuration is proposed to generate maximum power under PSCs and to minimize the number of cross ties and wiring complexities. This Configuration is an integration of TCT and BL PV Configuration and the simulation results prove the capability of this proposed PV Configuration to generate maximum power, fill factor, efficiency and minimum mismatching loss compared to S, SP, BL and HC PV Configurations under a majority of the PSCs investigated. A Canadian Solar CS5P-200M PV module is considered for simulation and is simulated using Matlab/Simulink software.

Index Terms—Alternate Total Cross Tied – Bridge Linked (A-TCT-BL) PV configuration, mismatching loss, partial shading conditions (PSCs), PV configurations.

NOMENCLATURE

I_{pv}	PV cell terminal current [A].
V	PV cell terminal voltage [V].
I_{ph}	Current generated by incident solar irradiation [A].
I_d	Diode current [A].
I_{sh}	Shunt current of a PV cell [A].
I_{sc}	Short circuit current of the cell [A].
K_i	Array short circuit current temperature coefficient.

T	Cell operating temperature [K].
H	Solar radiation in KW/m^2 .
I_o	Diode reverse leakage current [A].
K	Boltzmann's constant = $1.3806503 \times 10^{-23}$ J/K.
q	Electron charge = $1.60217646 \times 10^{-19}$ Coulombs.
A	Diode ideality factor.
R_s	Resistance of the PV cell connected in series [Ω].
R_{sh}	Resistance of the PV cell connected in parallel [Ω].
V_m	Module voltage [V].
I_m	Module current [A].
n	Number of strings connected in parallel .
m	Number of modules connected in parallel in a string.
p	Number of strings connected in series.
P_{max}	Maximum power of the array [W].
V_{max}	Maximum voltage of the array [V].
I_{max}	Maximum current of the array [A].
P_{max_u}	Maximum power of the array under uniform irradiance [W].
P_{max_i}	Sum of individual maximum power of the modules [W].
V_{oc}	Open circuit voltage of the array [V].
I_{sc}	Short circuit current of the array [A].
P_{GMPP}	Global maximum power point under PSCs [W].
N_s	Number of cells connected in series.
N_p	Number of cells connected in parallel.

I. INTRODUCTION

ENERGY consumption all over the world is significantly increasing. With this rate of energy consumption, fossil fuels will deplete in the near future. Renewable energy is the solution for today's conventional energy crisis [1].

Solar energy is one form of renewable energy which is gaining popularity due to its abundant availability, non-polluting nature and high reliability [2]. The performance and efficiency of PV systems depends on a number of factors, such as solar insolation, temperature, dust, aging factor, etc. Grid connected PV systems are often mounted on building roofs, facades or open spaces where partial shading frequently occurs. Partial shading can occur due to passing clouds, shadows of tall buildings or trees, bird droppings or also due to accumulation of dust or snow [3]. Hence this shading effect could be static or dynamic. Partial shading of PV cells gives rise

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to multiple peaks in I-V and P-V characteristics [4]. This reduces the output power and increases mismatching power losses. One method of tackling this problem is PV array Configuration Schemes [5]. Many Researchers have compared the performances of various PV Configurations and analyzed their behavior under partial shading scenarios.

O. Bingol *et al.* [1], analyzed and compared five PV Configurations S, SP, TCT, BL and HC under six shading conditions. The results proved that optimum output power was achieved by the TCT configuration under PSCs.

F. Belhachat *et al.* [3], modeled and analyzed six PV Configurations S, P, SP, TCT, BL and HC under various shading patterns. For most of the shading patterns, the TCT configuration gave the best performance. S. Bana *et al.* [5], investigated output power of various PV Configurations by conducting experiments under uniform and PSCs. Mohammad nejad *et al.* [6], demonstrated the analysis of TCT PV Configuration mathematically under PSCs and compared their performance with other PV Configurations such as SP, BL and HC.

H. Patel *et al.* [7], presented a MATLAB based model to study the partial shading effects on PV characteristics. N. D. Kaushika *et al.* [8], developed a computational network analysis approach to compare their configurations.

R. Ramaprabha *et al.* [9], investigated the effects of PSCs on energy output of PV Configurations. The authors developed a Matlab M-code for any array size, configuration and shading pattern. Y-J Wang *et al.* [10], [11], proposed analytical modeling of a PV to study the impact of partial shading and the different orientation of PV modules.

Dhimish M. *et al.* [12], analyzed S, P, SP, TCT and BL PV array configurations under faulty PV and partial shading conditions. Seven indicators were examined, namely short circuit current, open circuit voltage, maximum peak power current, maximum peak power voltage, series resistance, fill factor and thermal voltage. New mathematical calculations were formulated to estimate series resistance across one PV module in a PV array configuration.

P.R. Satpathy *et al.* [13], investigated the effect of partial shading on SP, BL and TCT PV Configurations. Power generated and mismatch loss were compared for the above PV Configurations using MATLAB/SIMULINK software and a prototype field experiment was conducted under different insolation and shading patterns. It was proved that TCT produced satisfactory results.

V. Jha *et al.* [14], compared the conventional PV Configurations S, P, SP, TCT, BL and HC with proposed hybrid PV Configurations SPTCT, BLTCT, HCTCT and BLHC. The authors concluded that TCT provides the best performance under PSCs followed by proposed hybrid PV Configurations. However TCT proved to be uneconomical due to greater amount of wiring and concluded that hybrid PV Configurations would be the best choice.

J.D.B-Rodriguez *et al.* [15], developed a general modeling procedure for photovoltaic array. This model could describe the behavior of regular and irregular PV Configurations.

M. Z. Shams El-Dein *et al.* [16], proposed a new mathematical formulation for the optimal reconfiguration of PV arrays

to reduce partial shading effects. The proposed formulation could be used for an equal or unequal number of modules per row.

G. Sai Krishna *et al.* [17], focused on reconfiguration techniques to increase maximum power under PSCs. The authors concluded that dynamic reconfiguration techniques, though expensive, are more effective in reducing partial shading effects than the static reconfiguration technique. Ram Tatabhatla V.M *et al.* [18], reconfigured TCT panels based on the Arrow Sudoku puzzle pattern. This reconfiguration minimized the current mismatch between rows.

From the above literature surveys, it is seen that there is a scope for analyzing the performance of the hybrid PV Configuration and comparing it with the conventional PV Configurations with a greater amount of PSCs to enhance the generated output power and lower mismatching loss. Taking inspiration from the above researches, this research paper focuses on the performance analysis of Series (S), Series Parallel (SP), Total Cross Tied (TCT), Bridge Linked (BL), Honey Comb (HC) and Alternate Total Cross Tied-Bridge Linked (A-TCT-BL) PV Configurations. A Six by six array is considered for investigation. A novel hybrid PV Configuration, called A-TCT-BL PV Configuration, is introduced in this paper. The performance of each PV Configuration under uniform insolation conditions is simulated and compared with PSCs. Nine PSCs, namely center, diagonal, corner, L-shaped, short and narrow, short and wide, long and narrow, long and wide and random are considered to study the effect of partial shading on the following PV array parameters: Open circuit voltage, Short circuit current, maximum voltage, maximum current, Global maximum power point (GMPP), Shading loss, Mismatching loss, Fill factor and Efficiency. Fig. 1 shows the classification of PV array configurations under various PSCs and parameters considered for comparing the performance assessment of PV array configurations.

II. MATHEMATICAL MODEL OF PV CELL, MODULE

Photovoltaic (PV) cells generate voltage when sunlight is incident on them. It is the basic building block for converting solar energy into electrical energy. Fig. 2(a) represents the equivalent circuit of PV cells as one diode model [19]. The circuit consists of a current generated by incident solar insolation called photo current (I_{ph}), a diode, a parallel resistance (R_{sh}) and a series resistance (R_s) representing the leakage current and an internal resistance respectively of the PV cell [20]. Each PV cell generates a small voltage of 0.6 V. These cells are connected in series and in parallel to increase the module voltage and module current respectively.

Figure 2(b) represents the equivalent circuit of the PV module with N_p cells connected in parallel and N_s cells connected in series. The mathematical equations that describes the I-V characteristics of PV cell are given by (1) to (4).

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (1)$$

$$I_{ph} = I_{sc} + K_i(T - 298)H \quad (2)$$

$$I_d = I_0 \left[\exp \left(\frac{(V + I_{pv}R_s)q}{AKT} \right) - 1 \right] \quad (3)$$

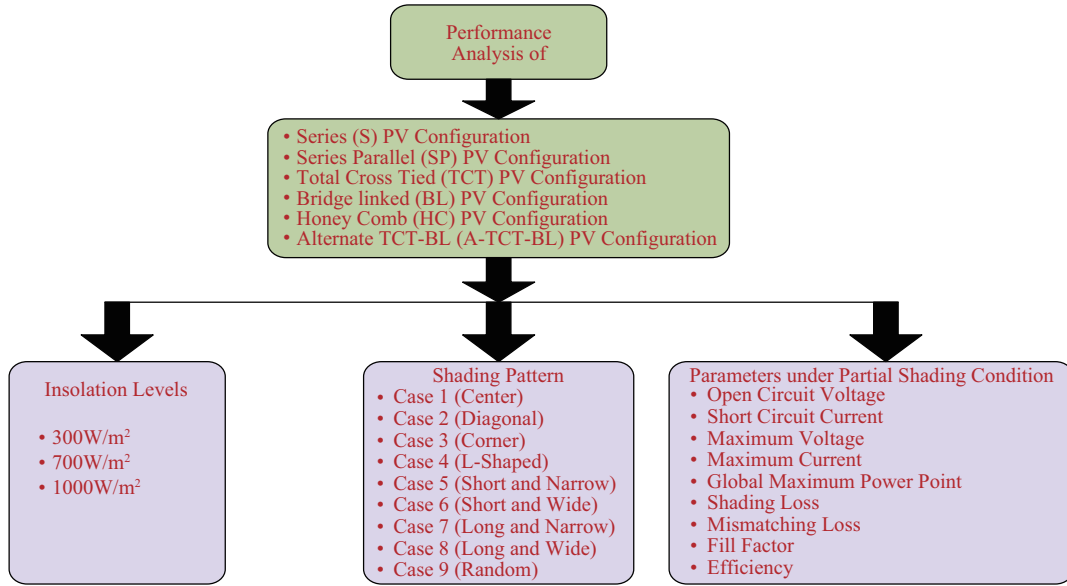


Fig. 1. Classification of PV configurations under various PSCs, insolation levels, shading pattern and parameters considered for comparing and analyzing the performance of PV configurations.

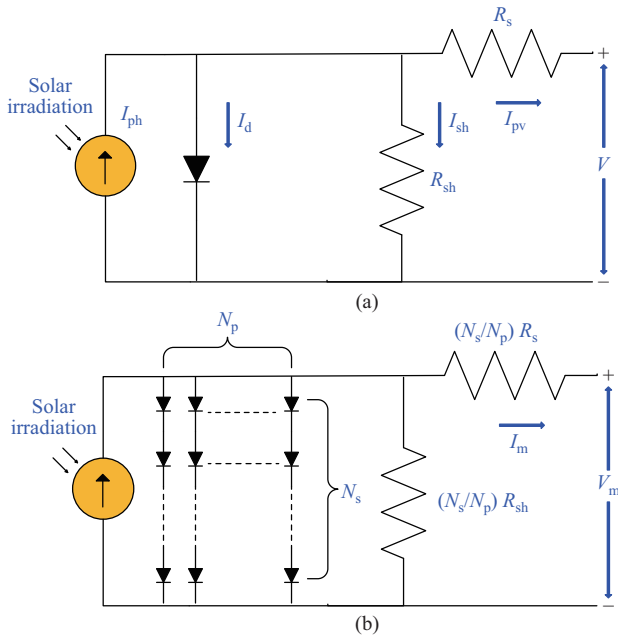


Fig. 2. (a) Equivalent circuit model of PV cell, (b) Equivalent circuit of PV module.

$$I_{sh} = \frac{V + I_{pv}R_s}{R_{sh}} \quad (4)$$

where I_{pv} is the terminal current of the PV cell; I_{ph} is the current generated by the incident solar irradiance, I_d is the diode current and I_{sh} is the shunt resistance current; I_{sc} is the short circuit current of the cell, K_i is the array short circuit current temperature coefficient, T is the cell operating temperature (K), H is the solar radiation in KW/m^2 ; I_o is the diode reverse leakage current, V is the terminal voltage, K is Boltzmann's constant ($1.3806503 \times 10^{-23}$ J/K) [21], q is the electron charge ($1.60217646 \times 10^{-19}$ C); R_{sh} and R_s are the shunt and series resistances of the PV cell in Ω and A is the

diode ideality factor and its ideal value is 1.

The mathematical equation that describes the I-V characteristics of PV module is given by (5) [1]:

$$I_m = N_p I_{ph} - N_p I_0 \left[\exp \left(\frac{q}{AKT} \left(\frac{V_m}{N_s} + \frac{I_m R_s}{N_p} \right) \right) - 1 \right] - \frac{\frac{N_p}{N_s} V_m + I_m R_s}{R_{sh}} \quad (5)$$

where I_m is the terminal current of the PV module; V_m is the terminal voltage of the PV module.

PV module is modeled in MATLAB/Simulink to obtain the I-V and P-V characteristics. Fig. 3(a) and Fig. 3(b) represent the I-V and P-V characteristics of the PV module for different insolation conditions. The datasheet of the PV module Canadian Solar CS5P-200 M is given in Appendix.

III. TERMS AND DEFINITIONS PERTAINING TO THE PV ARRAY

A. Shading Power Loss

It is the difference between maximum power of the array under uniform irradiance and the sum of individual maximum power of modules available for each shading pattern.

It is given by the following equation:

$$P_{\text{shading loss}} = P_{\text{max}_u} - P_{\text{max}_i} \quad (6)$$

where P_{max_u} is the maximum power under uniform irradiance and P_{max_i} is the sum of individual maximum power of modules available in an array for each shading pattern.

B. Mismatching Power Loss

It is defined as the difference between the sum of individual maximum power of modules available in an array for each shading pattern and the Global maximum power point under each PSC.

$$\text{mismatching loss} = \frac{(P_{\text{max}_i} - P_{\text{GMPP}})}{P_{\text{max}_i}} \quad (7)$$

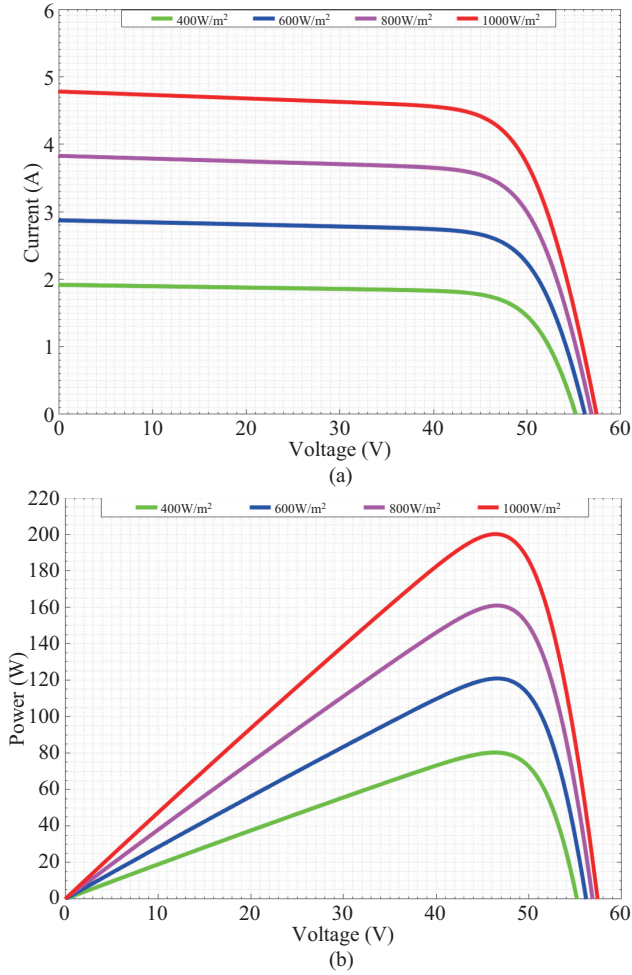


Fig. 3. (a) I-V and (b) P-V characteristics of the PV module for different insolation conditions.

C. Fill Factor

Fill factor (FF) is defined as the ratio of maximum power to the theoretical power which is the product of the open circuit voltage and short circuit current of the PV Configuration under PSCs [22].

$$\text{Fill Factor} = \frac{P_{\text{GMPP}}}{V_{\text{oc}} I_{\text{sc}}} \quad (8)$$

D. Efficiency of PV Array Configuration

It is defined as the ratio of output power to input power. Here output power is the Global maximum power under each PSC in watts. Input power is insolation in Watts/m² across each module multiplied by the module area [23].

$$\text{Efficiency} = \frac{P_{\text{GMPP}}}{I \times A} \quad (9)$$

where I is the input solar insolation across each module and A is the module area.

IV. DESCRIPTION OF VARIOUS PARTIAL SHADING CONDITIONS (PSCs)

The PV array output power decreases when the PV panels are partially shaded. PSCs arise due to the shading effect

caused by passing clouds, shadows of trees, shadows of tall building, snow or due to bird droppings.

Due to PSCs, the irradiation falling on the PV panels is non-uniform and hence it gives rise to multiple peak output power. These multiple peaks are responsible for increasing the mismatching loss and shading loss. The efficiency of the PV array thereby reduces, producing less output power. Following nine cases of shading patterns for three levels of insolation namely 300 W/m², 700 W/m² and 1000 W/m² are discussed in detail for carrying out the analysis of various PV

Configurations on a six by six array.

Case 1 (center): The solar insolation on the 4 modules at the center namely module number PV15, PV 16, PV21 and PV22 is 300 W/m². The insolation on the immediate neighboring modules i.e PV 8, PV 9, PV 10, PV11, PV 14, PV 17, PV 20, PV 23, PV 26, PV 27, PV 28 and PV 29 are 700 W/m² and on the remaining modules are 1000 W/m². This is shown in Fig. 4(a).

Case 2 (diagonal): Left side diagonally arranged 6 modules namely PV 1, PV 8, PV 15, PV 22, PV 29 and PV 36 have solar insolation of 300 W/m². Whereas the adjacent modules on either side of the diagonal namely PV 7, PV 14, PV 21, PV 28, PV 35, PV 2, PV 9, PV 16, PV 23, and PV 30 have solar insolation of 700 W/m². The rest of the modules are subjected to 1000 W/m². This is shown in Fig. 4(b).

Case 3 (corner): The four corner modules namely PV 1, PV 6, PV 31 and PV 36 are subjected to 300 W/m². The three modules surrounding each corner module have insolation of 700 W/m². The remaining modules have an insolation of 1000 W/m². This is shown in Fig. 4(c).

Case 4 (L-shaped): First two rows and first two columns namely PV 1 to PV 12, PV 13–14, PV 19–20, PV 25–26 and PV 31–32 have solar insolation of 300 W/m². The modules in the immediate neighborhood i.e. PV 15–18, PV 21, PV 27 and PV 33 have solar insolation of 700 W/m². The rest of the modules have insolation of 1000 W/m². This is shown in Fig. 4(d).

Case 5 (short and narrow): First three modules of first and second column respectively namely PV 1–3, PV 7–9 have solar insolation of 300 W/m². First three modules of third column i.e PV 13–15 have solar insolation of 700 W/m². The remaining modules have an insolation of 1000 W/m². This is shown in Fig. 4(e).

Case 6 (short and wide): First three modules of first, second and third column respectively i.e PV 1–3, PV 7–9, PV 13–15 have solar insolation of 300 W/m². First three modules of fourth and fifth column respectively i.e PV 19–21, PV 25–27 have solar insolation of 700 W/m². The remaining modules have an insolation of 1000 W/m². This is shown in Fig. 4(f).

Case 7 (long and narrow): First five modules of first and second column respectively i.e PV 1–5, PV 7–11 have solar insolation of 300 W/m². First five modules of third column i.e PV 13–17 have solar insolation of 700 W/m². The remaining modules have an insolation of 1000 W/m². This is shown in Fig. 4(g).

Case 8 (long and wide): First five modules of first, second and third column respectively i.e PV 1–5, PV 7–11, PV 13–17 have solar insolation of 300 W/m². First five modules of

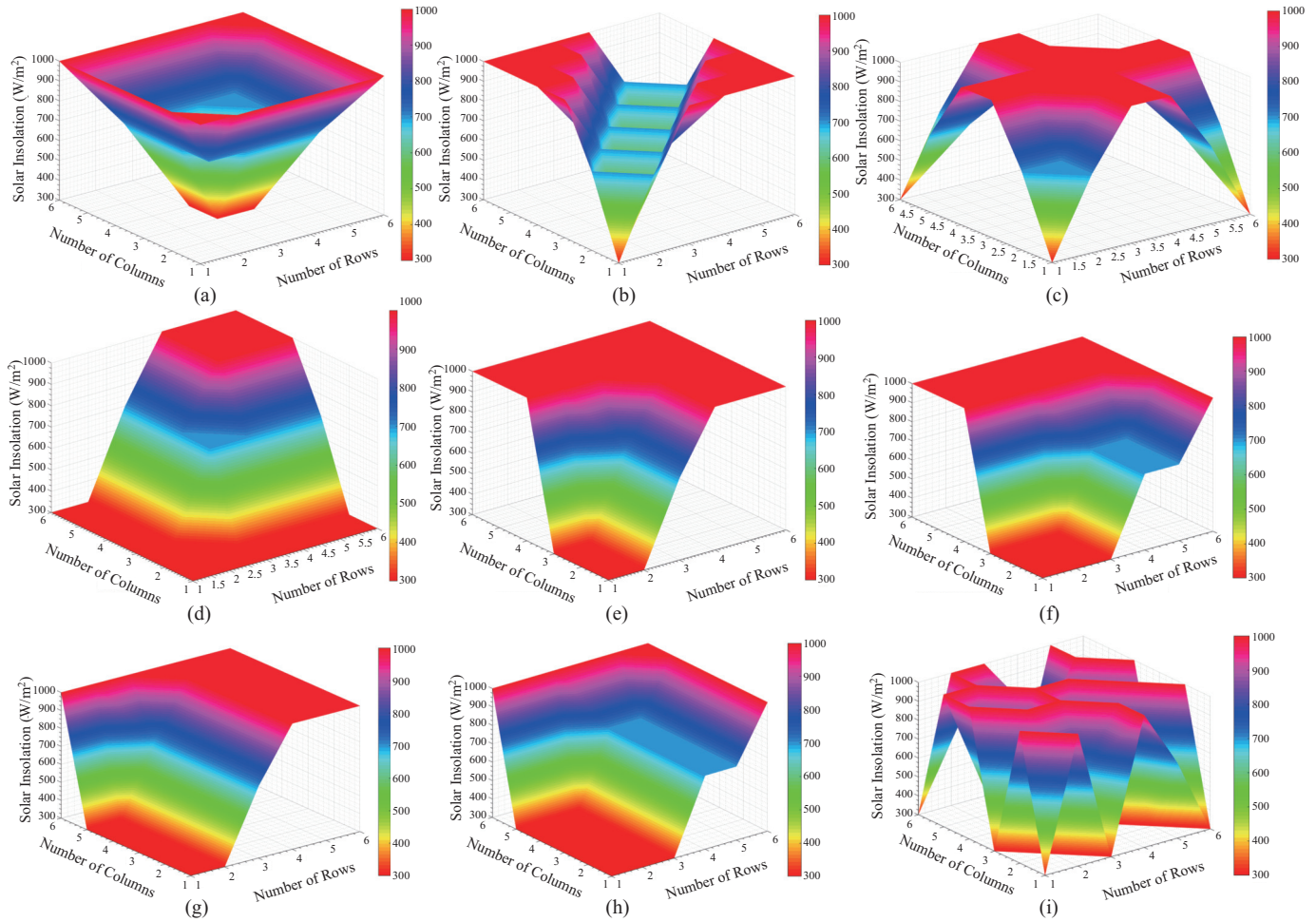


Fig. 4. Representation of various shading patterns under PSCs: (a) case 1 (b) case 2 (c) case 3 (d) case 4 (e) case 5 (f) case 6 (g) case 7 (h) case 8 (i) case 9.

fourth and fifth column respectively i.e PV 19–23, PV 25–29 have solar insolation of 700 W/m². The remaining modules have an insolation of 1000 W/m². This is shown in Fig. 4(h).

Case 9 (random): The solar insolation on the PV modules is random. PV 1, 3, 6, 8, 10, 13, 17, 21, 24, 26, 28, 31, 33 and 36 have solar insolation of 300 W/m². PV 14, 23, 25 and 35 have solar insolation of 700 W/m². The rest of the modules have insolation of 1000 W/m². This is shown in Fig. 4(i).

V. MODELING AND SIMULATION OF PV ARRAY CONFIGURATIONS

A. Series (S) PV Configuration

All of the 36 modules are connected in series in this configuration as shown in Fig. 5. Hence the array current remains the same as the module current or cell current but the array voltage is the sum of the individual module voltages under uniform irradiation. Let I_m and V_m be the maximum values of the module current and module voltage respectively. For n number of strings, the array current (I_{array}), array voltage (V_{array}) and array power (P_{array}) is given by the following equations [24]:

$$I_{array} = I_{string} = I_m \quad (10)$$

$$V_{array} = \sum_{i=1}^{36} V_{mi} = 36V_m \quad (11)$$

$$P_{array} = (V_{array})(I_{array}) = 36V_m I_m \quad (12)$$

It is seen that at PSC case 5, the Series PV Configuration generates maximum output power of 5368.7 W and at case 4 it generates minimum output power of 2377.9 W. The lowest insolation level determines the series PV array current. In order to generate short circuit current equal to unshaded PV module current, the shaded modules operate in a reverse bias condition. Hence they dissipate the power in the form of heat instead of delivering the power. This heat causes hot spots on the module which can ultimately damage the module. The module is protected against these hotspots by providing an alternate path for the current flow by connecting bypass diodes in antiparallel against the module [25], [26]. The drawback of a Series PV Configuration is that it generates less current and mismatching losses are high due to the greater number of series connections. The I-V and P-V characteristics under nine different PSCs for the Series PV Configuration are shown in Fig. 6(a) and (b). It is visible in the P-V characteristics that due to partial shading and due to the presence of a bypass diode, multiple peaks are produced in the graph. The highest



Fig. 5. MATLAB/Simulink model of 6 × 6 Series (S) PV array configuration.

peak represents peak power and is called GMPP and the rest of the peaks are called Local maximum power point (LMPP). LMPP and GMPP for a few PSCs are highlighted in the P-V characteristics of Fig. 6(b). Also highlighted are maximum voltage and current values in the I-V characteristics of Fig. 6(a) corresponding to these GMPP values.

B. Series Parallel (SP) PV Configuration

In this configuration, the desired output voltage is available by connecting a number of PV modules in series to form a string. These strings are then connected in parallel to obtain the desired output current [9]. In the MATLAB/ Simulink model of 6 x 6 Series Parallel (SP) PV Configuration, six PV modules are connected in series to form a string. The six strings are then connected in parallel to generate the required output current as shown in Fig. 7. The I-V and P-V characteristics under nine different PSCs for the SP PV Configuration are shown in Fig. 8(a) and (b).

The array current (I_{array}), array voltage (V_{array}) and array power (P_{array}) are given by the following equations:

$$I_{array} = I_1 + I_2 + I_3 + I_4 + I_5 + I_6 = n(I_{string}) = 6I_m \quad (13)$$

$$V_{array} = V_{string} = \sum_{i=1}^6 V_{mi} = 6V_m \quad (14)$$

$$P_{array} = (V_{array})(I_{array}) = 36V_m I_m \quad (15)$$

where n is the number of strings connected in parallel. The performance of the SP PV Configuration is better than the S PV Configuration since the desired voltage and current is achieved by connecting modules in series and parallel respectively. However the drawback is that it develops high mismatching loss and low efficiency under PSCs.

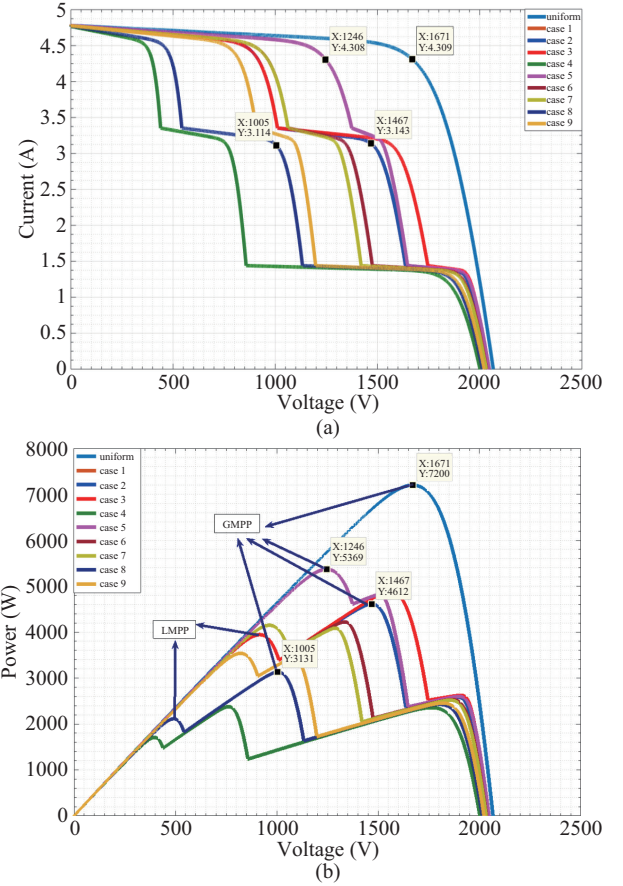


Fig. 6. (a) I-V (b) P-V Characteristics of Series 6 × 6 configuration under various partial shading conditions.

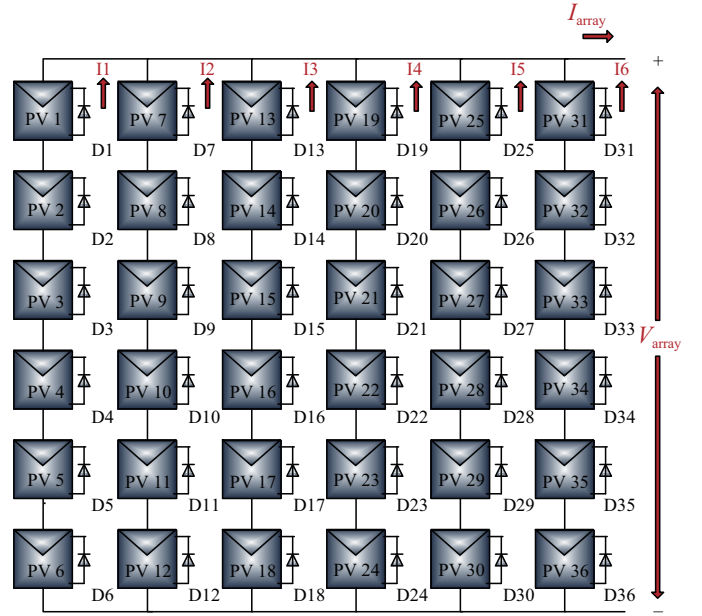


Fig. 7. MATLAB/Simulink model of 6 × 6 Series Parallel (SP) PV array configuration.

C. Total Cross Tied (TCT) PV Configuration

The TCT PV configuration has cross ties in it and is basically derived from a SP configuration. TCT is a series

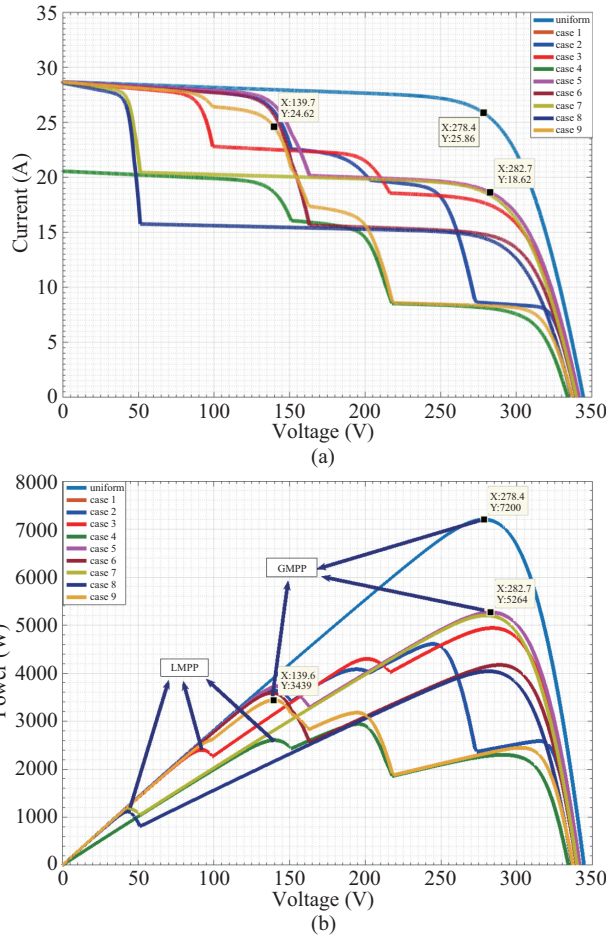


Fig. 8. (a) I-V (b) P-V Characteristics of Series Parallel 6×6 configuration under various partial shading conditions.

connection of parallel strings. In the 6×6 array configuration, 6 modules are connected in parallel. The 6 strings of parallel connected modules are then connected in series as shown in Fig. 9.

The current in each string is equal to the sum of a six module current. Hence the array current is equal to the string current. Each string voltage is equal to the module voltage, whereas the array voltage is equal to the sum of the six string voltages [22].

The array current (I_{array}), array voltage (V_{array}) and array power (P_{array}) is given by the following equations:

$$I_{array} = mI_{string} = 6I_m \quad (16)$$

$$V_{array} = p(V_{string}) = 6V_m \quad (17)$$

$$P_{array} = (V_{array})(I_{array}) = 36V_m I_m \quad (18)$$

where m is the number of modules connected in parallel in a string and p is the number of strings connected in series.

I-V and P-V characteristics under nine different PSCs for TCT PV Configuration are shown in Fig. 10(a) and (b). GMPP and LMPP are shown in the P-V characteristics in Fig. 10(b). It is seen that the TCT PV Configuration produces high GMPP compared to other PV Configurations under PSCs. But the number of cross ties present are 25, which means it requires more wires.

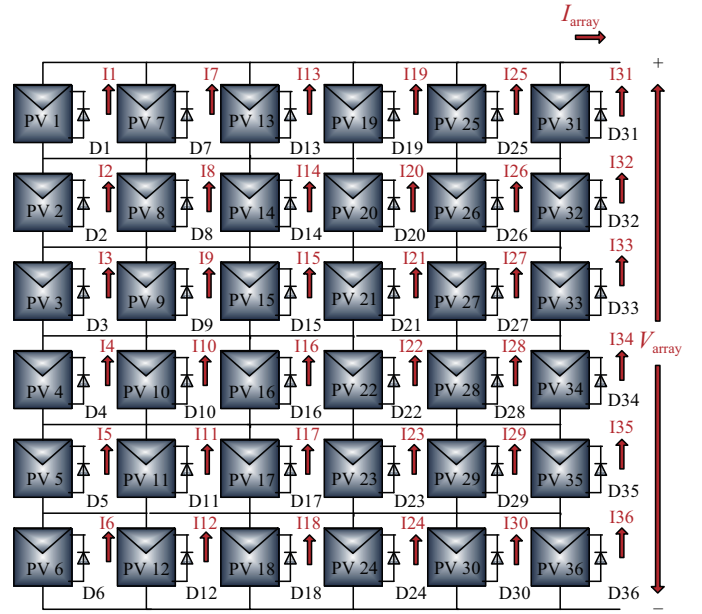


Fig. 9. MATLAB/Simulink model of 6×6 TCT PV array configuration.

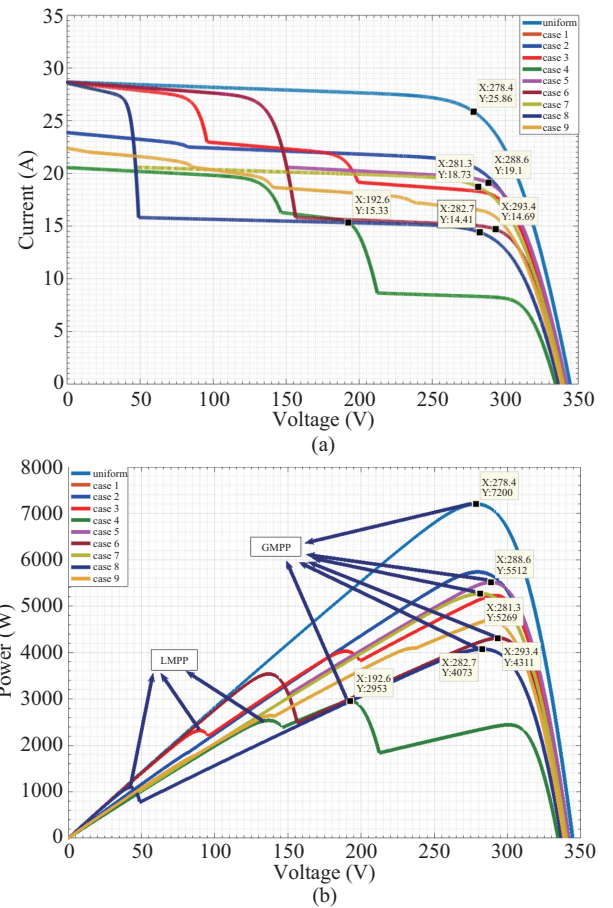
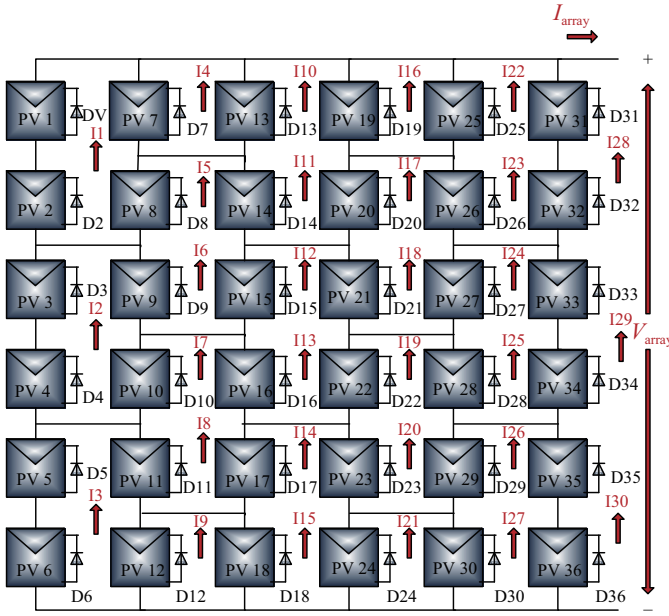


Fig. 10. (a) I-V (b) P-V Characteristics of the Total Cross Tied 6×6 configurations under various partial shading conditions.

D. Bridge Linked (BL) PV Configuration

In this configuration, as the name implies, the modules are connected just like a bridge as shown in Fig. 11. Two

Fig. 11. MATLAB/Simulink model of 6×6 BL PV array configuration.

modules are first connected in series. The two sets of the series connected modules are then connected in parallel with each other. The number of cross ties present in the 6×6 BL PV Configuration are 12. These are less as compared to the T-C-T and H-C Configurations. Hence wiring cost is less. But the mismatching losses are more compared to the TCT and B- L Configurations and are less compared to the S and S-P Configurations due to a fewer number of cross ties.

The array current (I_{array}), array voltage (V_{array}) and array power (P_{array}) are given by the following equations:

$$I_{array} = I_1 + I_4 + I_{10} + I_{16} + I_{22} + I_{28} = 6I_m \quad (19)$$

$$V_{array} = 6V_m \quad (20)$$

$$P_{array} = (V_{array})(I_{array}) = 36V_m I_m \quad (21)$$

I-V and P-V characteristics under nine different PSCs for the BL PV Configurations are shown in Fig. 12(a) and 12(b). Also shown are the GMPP and LMPP points for various partial shading conditions of the P-V characteristics.

E. Honey Comb (HC) PV Configuration

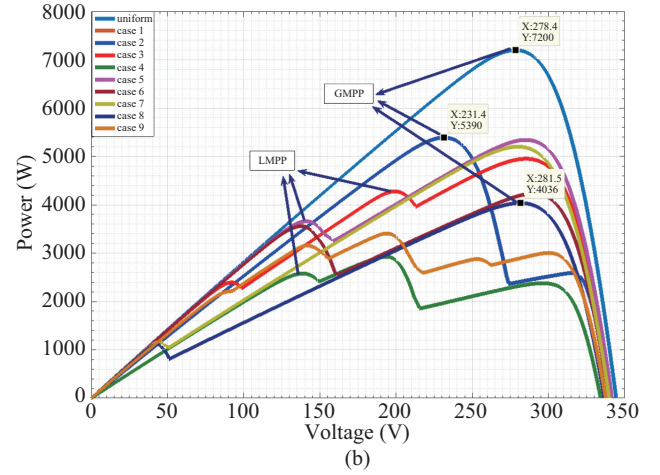
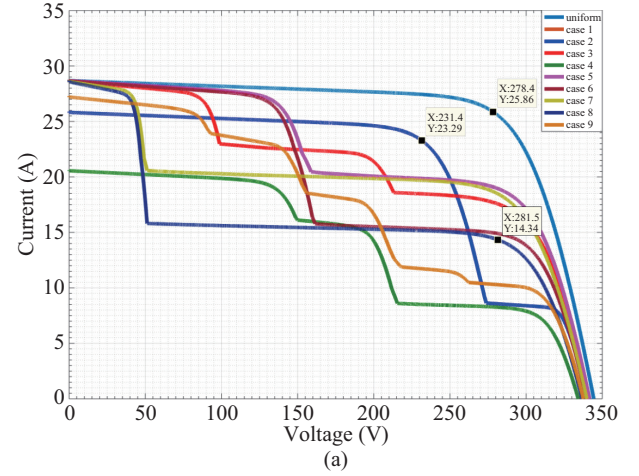
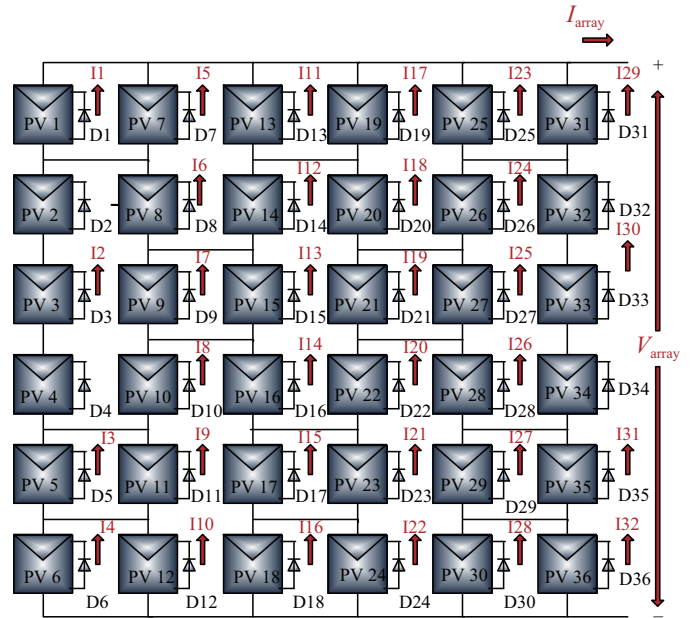
As the name suggests, all the modules are interconnected in a hexagonal shape similar to a honey comb. This is shown in Fig. 13.

The interconnections in this configuration are more than the S and S-P configurations. The series connections are less than the S and S-P configurations. Hence the mismatching power losses are less as compared to the S and SP PV Configurations. I-V and P-V characteristics under nine different PSCs for the HC PV Configuration are shown in Fig. 14(a) and (b). The array current (I_{array}), array voltage (V_{array}) and array power (P_{array}) are given by the following equations:

$$I_{array} = I_1 + I_5 + I_{11} + I_{17} + I_{23} + I_{29} = 6I_m \quad (22)$$

$$V_{array} = 6V_m \quad (23)$$

$$P_{array} = (V_{array})(I_{array}) = 36V_m I_m \quad (24)$$

Fig. 12. (a) I-V (b) P-V Characteristics of Bridge Linked 6×6 configuration under various partial shading conditions.Fig. 13. MATLAB/Simulink model of a 6×6 HC PV array configuration.

The total number of cross ties present in the 6×6 HC PV Configuration are 13.

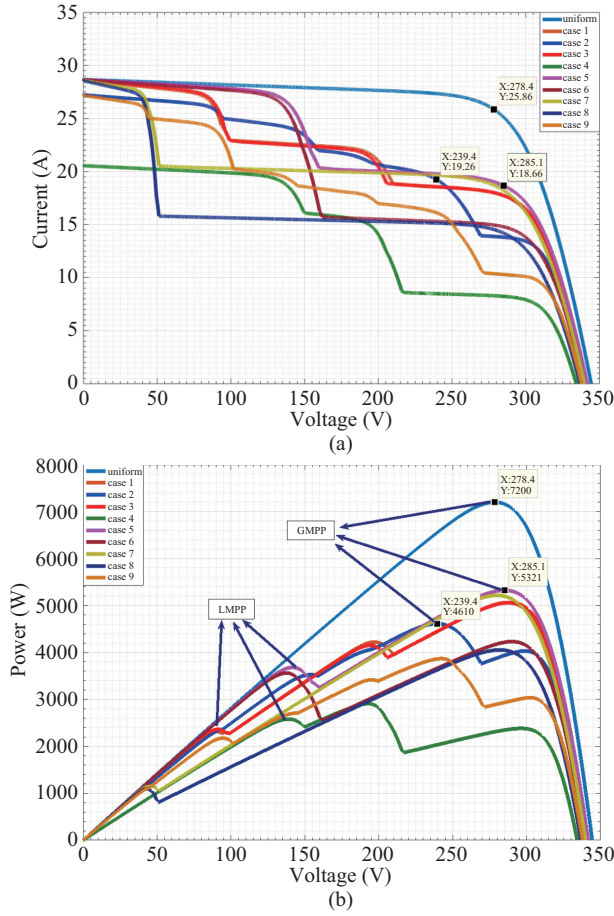


Fig. 14. (a) I-V (b) P-V characteristics of honey comb 6×6 configuration under various partial shading conditions.

F. Alternate TCT-BL (A-TCT-BL) PV Configuration

This configuration is novel in its type and is formed by alternately connecting two columns of arrays in the TCT configuration and the next two columns in the BL configuration. This is shown in Fig. 15. In the 6×6 TCT PV configuration, the total number of cross ties are 25 which are more and hence requires more wires for connection. In this PV configuration, an attempt is made to reduce the requirement of wires thereby reducing its complexity, but still maintaining its performance, which is better than the BL and HC PV Configurations in terms of extracting maximum output power under PSCs and at par with the TCT PV configuration.

The A-TCT-BL PV Configuration, being a combination of TCT and BL with specific locations of cross ties, has the advantages of both the TCT and BL PV Configurations. This is due to the fact that the total number of cross ties present in the 6×6 A-TCT-BL PV Configuration is 19, which is more than the BL and HC PV Configurations, but less than the TCT PV Configuration. Owing to more number of cross ties compared to the BL and HC PV Configurations, this novel PV Configuration performs better than S, SP, BL and HC PV Configurations under most of the PSCs. I-V and P-V characteristics under nine different PSCs for the A-TCT-BL PV Configuration are shown in Fig. 16(a) and (b). The array current (I_{array}), array voltage (V_{array}) and array power (P_{array})

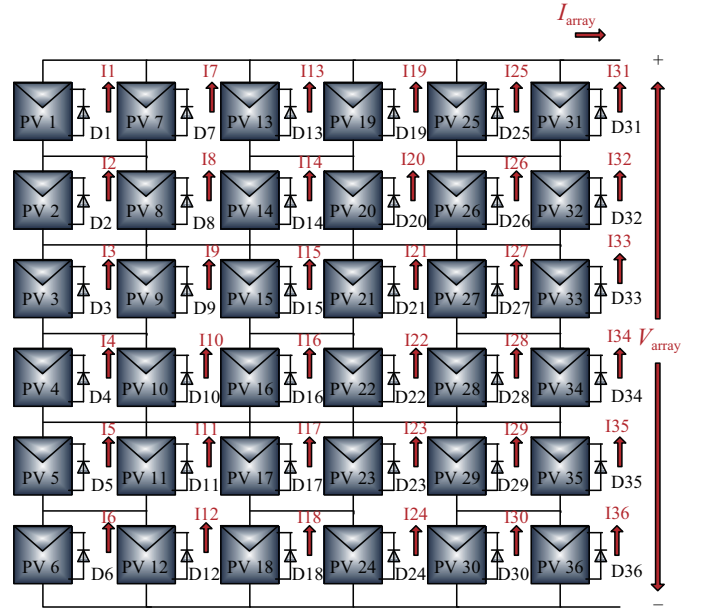


Fig. 15. MATLAB/Simulink model of 6×6 alternate TCT-BL PV array configuration.

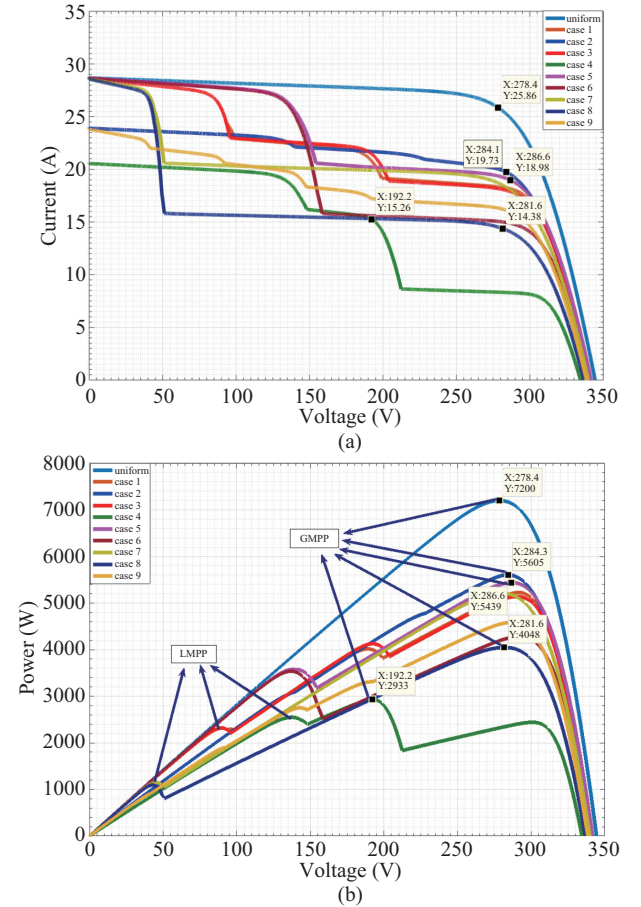


Fig. 16. (a) I-V (b) P-V characteristics of alternate TCT-BL 6×6 Configuration under various partial shading conditions.

are given by the following equations:

$$I_{array} = I_1 + I_7 + I_{13} + I_{19} + I_{25} + I_{31} = 6I_m \quad (25)$$

$$V_{\text{array}} = 6V_m \quad (26)$$

$$P_{\text{array}} = (V_{\text{array}})(I_{\text{array}}) = 36V_m I_m \quad (27)$$

VI. PERFORMANCE ASSESSMENT OF PV CONFIGURATIONS UNDER DIFFERENT PARTIAL SHADING CONDITIONS (PSCs)

S, SP, TCT, HC, BL and A-TCT-BL PV Configurations are compared to study their performance under uniform insolation conditions and PSCs. The parameters considered to analyze the performance are maximum power, maximum voltage, maximum current, global maximum power point, shading power loss, mismatching power loss, fill factor and efficiency.

A. Maximum Voltage, Maximum Current, Maximum Power

S, SP, TCT, HC, BL and A-TCT-BL PV Configurations generate a maximum power of 7199.6 Watts under uniform irradiance conditions. Maximum voltage is 278.407 V and maximum current is 25.859 A under uniform irradiance conditions for SP, TCT, HC, BL and A-TCT-BL PV Configurations, whereas the S PV Configuration has maximum voltage and current of 1670.5 V and 4.309 A respectively.

Values of maximum power (P_{max}), maximum voltage (V_{max}) and maximum current (I_{max}) for various PV configurations under nine PSCs are shown in Table I.

In case 1 (center) PSC, TCT PV Configurations generate maximum power of 5227.7 W followed by A-TCT-BL (5225.2 W), HC (5060.2 W), BL (4951.4 W), SP (4940.7 W) and S (4892.6 W). Therefore TCT generates 6.41%, 5.5%, 5.28%, 3.2% and 0.04% more power than the S, SP, BL, HC and A-TCT-BL PV Configurations respectively.

In case 2 (diagonal) PSC, TCT PV Configurations generate maximum power of 5734.7 W followed by A-TCT-BL (5604.7 W), BL (5390.4 W), S (4612.0 W), HC (4610.4 W) and SP (4606.7 W). Hence TCT generates 19.66%, 19.60%,

19.57%, 6.0% and 2.26% more power than the SP, HC, S, BL and A-TCT-BL PV Configurations respectively.

In case 3 (corner) PSC, TCT PV Configurations generate maximum power of 5227.7 W followed by A-TCT-BL (5138.7 W), HC (5061.5 W), BL (4951.4 W), SP (4940.7 W) and S (4892.6 W). Therefore TCT generates 6.41%, 5.5%, 5.28%, 3.17% and 1.7% more power than the S, SP, BL, HC and A-TCT-BL PV Configurations respectively.

In case 4 (L-shaped) PSC, TCT PV Configurations generate maximum power of 2953.3 W followed by SP (2940.2 W), A-TCT-BL (2933 W), BL (2926.9 W), HC (2907.9 W) and S (2377.9 W). Therefore TCT generates 19.48%, 1.53%, 0.89%, 0.68% and 0.44% more power than the S, HC, BL, A-TCT-BL and SP PV Configurations respectively.

In case 5 (short and narrow) PSC, TCT PV Configurations generate maximum power of 5511.9 W followed by A-TCT-BL (5439.5 W), S (5368.7 W), BL (5340.1 W), HC (5321.4 W) and SP (5264.4 W). Hence TCT generates 4.49%, 3.45%, 3.11%, 2.59% and 1.31% more power than the SP, HC, BL, S and A-TCT-BL PV Configurations respectively.

In case 6 (short and wide) PSC, TCT PV Configurations generate maximum power of 4310.6 W followed by A-TCT-BL (4282.1 W), BL (4231.5 W), HC (4229.1 W), S (4222.5 W) and SP (4170.7 W). Therefore TCT generates 3.24%, 2.04%, 1.89%, 1.83% and 0.66% more power than the SP, S, HC, BL and A-TCT-BL PV Configurations respectively.

In case 7 (long and narrow) PSC, TCT PV Configurations generate maximum power of 5269.1 W followed by HC (5214.1 W), A-TCT-BL (5210.5 W), SP (5203.4 W), BL (5201.9 W) and S (4148.1 W). Hence TCT generates 21.27%, 1.27%, 1.24%, 1.11% and 1.04% more power than the S, BL, SP, A-TCT-BL and HC PV Configurations respectively.

In case 8 (long and wide) PSC, TCT PV Configurations generate maximum power of 4072.7 W followed by HC (4052.7 W), A-TCT-BL (4048.2 W), SP (4038.6 W), BL (4036.2 W) and S (3130.8 W). Hence TCT generates 23.12%,

TABLE I
VALUES OF MAXIMUM POWER, MAXIMUM VOLTAGE AND MAXIMUM CURRENT FOR VARIOUS PV CONFIGURATIONS UNDER PSCs

Shading Pattern	Case 1			Case 2			Case 3		
	P_{max}	V_{max}	I_{max}	P_{max}	V_{max}	I_{max}	P_{max}	V_{max}	I_{max}
S	4892.6	1560.9	3.1345	4612.0	1467.5	3.1427	4892.6	1560.9	3.1345
S-P	4940.7	283.90	17.402	4606.7	244.65	18.829	4940.7	283.90	17.40
T-C-T	5227.7	291.46	17.936	5734.7	279.58	20.511	5227.7	291.46	17.936
B-L	4951.4	285.23	17.359	5390.4	231.49	23.285	4951.4	285.23	17.359
H-C	5060.2	286.75	17.646	4610.4	239.41	19.256	5061.5	288.52	17.542
A-TCT-BL	5225.2	291.34	17.935	5604.7	284.112	19.726	5138.7	290.237	17.705
	Case 4			Case 5			Case 6		
	P_{max}	V_{max}	I_{max}	P_{max}	V_{max}	I_{max}	P_{max}	V_{max}	I_{max}
S	2377.9	761.96	3.1207	5368.7	1246.0	4.308	4222.5	1333.5	3.1665
S-P	2940.2	195.42	15.04	5264.4	282.71	18.62	4170.7	288.61	14.451
T-C-T	2953.3	192.60	15.333	5511.9	288.69	19.09	4310.6	293.40	14.691
B-L	2926.9	193.37	15.136	5340.1	285.09	18.73	4231.5	290.09	14.586
H-C	2907.9	192.81	15.081	5321.4	285.16	18.66	4229.1	289.90	14.588
A-TCT-BL	2933	192.2	15.26	5439.5	286.66	18.974	4282.1	291.917	14.668
	Case 7			Case 8			Case 9		
	P_{max}	V_{max}	I_{max}	P_{max}	V_{max}	I_{max}	P_{max}	V_{max}	I_{max}
S	4148.1	963.06	4.307	3130.8	1005.4	3.114	3537.7	821.68	4.305
S-P	5203.4	279.79	18.597	4038.6	281.50	14.346	3439.3	139.66	24.625
T-C-T	5269.1	281.34	18.728	4072.7	282.74	14.404	4692.0	288.13	16.283
B-L	5201.9	279.93	18.582	4036.2	281.54	14.336	3406.3	193.79	17.576
H-C	5214.1	279.89	18.628	4052.7	281.78	14.382	3867.6	242.34	15.959
A-TCT-BL	5210.5	279.80	18.621	4048.2	281.68	14.371	4583.3	286.37	16.004

TABLE II
 $P_{\max_i}$ (WATTS) FOR EACH SHADING PATTERN

Shading Pattern	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
$P_{\max_i}$	5930.412	5768.208	5930.412	3983.241	6181.551	5583.951	5502.849	4506.849	5001.294

0.89%, 0.83%, 0.6% and 0.49% more power than the S, BL, SP, A-TCT-BL and HC PV Configurations respectively.

In case 9 (random) PSC, TCT PV Configurations generate maximum power of 4692 W followed by A-TCT-BL (4583.3 W), HC (3867.6 W), S (3537.7 W), SP (3439.3 W) and BL (3406.3 W). Therefore TCT generates 27.4%, 26.69%, 24.6%, 17.57% and 2.31% more power than the BL, SP, S, HC and A-TCT-BL PV Configurations respectively.

B. Shading Power Loss

The sum of individual maximum power of modules available in an array for each shading pattern ($P_{\max_i}$) is given in Table II and is calculated from the maximum power of the individual module.

The values for shading power loss for various PV configurations are given graphically and are shown in Fig. 17. The shading power loss is maximum in case 4 (L-shaped) shading pattern and is 3216.359 W whereas it is minimum in case 5 (short and narrow) shading pattern and is equal to 1018.049 W. It is seen that the shading power loss remains the same for all PV configurations for a given shading pattern.

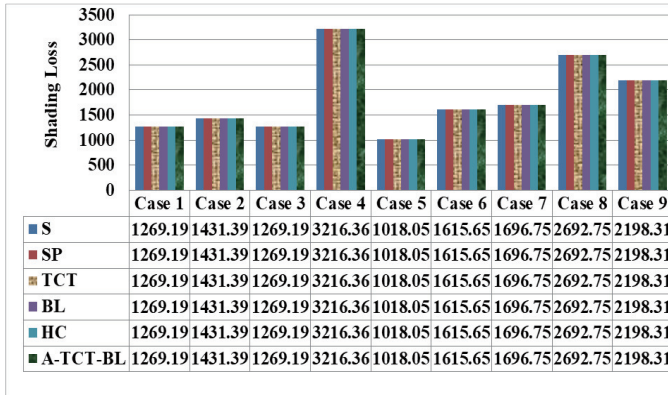


Fig. 17. Shading Loss of PV Configurations for different shading patterns.

C. Global Maximum Power Point (GMPP)

It is the maximum power generated by the PV array among the multiple peaks generated under partial shaded conditions. Multiple peaks are produced due to the presence of the bypass diode connected in antiparallel across each module. Values of GMPP are indicated in the table for different shading conditions and PV Configurations in Fig. 18. It is also represented graphically. It is observed that GMPP is maximum for all shading patterns for TCT PV Configurations. The A-TCT-BL PV Configuration shows GMPP values very close to TCT values with a difference ranging between 2.5 W to 130 W only depending on the nature of the PSCs. The A-TCT-BL PV Configuration proves to be the second best in extracting maximum power under most of the PSCs.



Fig. 18. GMPP of PV Configurations for different shading patterns.

D. Mismatching Power Loss

Mismatching Power Losses are indicated in the table of Fig. 19 for different shading patterns and PV Configurations. It is also represented graphically in the same figure. It is observed that Mismatching Power Loss is minimum for the TCT PV Configuration under all PSCs. A-TCT-BL shows the second best results for mismatching power loss under all PSCs except in case 4 where the SP generates less mismatching loss compared to A-TCT-BL and in case 7 and case 8 where HC generates less mismatching loss compared to A-TCT-BL PV Configuration.

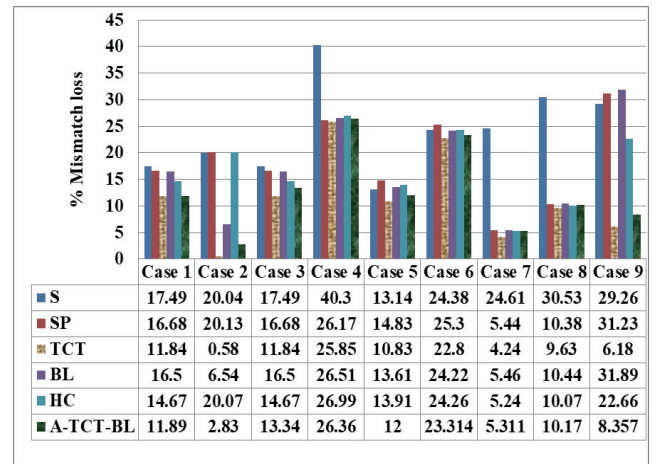


Fig. 19. Mismatching power loss of PV Configuration for different shading patterns.

E. Fill Factor

The table in Fig. 18 indicates the GMPP for various PV Configurations under PSCs. Table III denotes the open circuit voltage and short circuit current of the array under various PSCs. The table in Fig. 20 denotes the values of Fill Factor for all PSCs for various PV Configurations. It is found that

TABLE III
OPEN CIRCUIT VOLTAGE IN VOLTS AND SHORT CIRCUIT CURRENT IN AMPERES FOR VARIOUS PV CONFIGURATIONS UNDER DIFFERENT SHADING PATTERNS

Shading Patterns	Parameter	S	SP	TCT	BL	HC	A-TCT-BL
Case 1	V_{oc}	2044.2	340.987	341.18	341.04	341.075	341.18
	I_{sc}	4.791	28.737	28.726	28.735	28.726	28.726
Case 2	V_{oc}	2040	340.025	340.86	340.112	340.427	340.847
	I_{sc}	4.791	28.745	23.939	25.883	27.304	23.962
Case 3	V_{oc}	2044.2	340.987	341.18	341.04	341.11	341.162
	I_{sc}	4.791	28.737	28.726	28.735	28.733	28.726
Case 4	V_{oc}	2001.6	334.057	334.47	334.25	334.232	334.477
	I_{sc}	4.785	20.606	20.601	20.605	20.605	20.603
Case 5	V_{oc}	2046.2	341.495	341.74	341.617	341.60	341.67
	I_{sc}	4.792	28.751	28.743	28.748	28.749	28.745
Case 6	V_{oc}	2034.8	339.57	339.83	339.675	339.657	339.762
	I_{sc}	4.791	28.745	28.743	28.744	28.744	28.743
Case 7	V_{oc}	2032.7	339.867	339.99	339.90	339.885	339.90
	I_{sc}	4.791	28.718	28.677	28.708	28.701	28.694
Case 8	V_{oc}	2013.8	336.665	336.78	336.70	336.717	336.735
	I_{sc}	4.787	28.691	28.677	28.685	28.677	28.677
Case 9	V_{oc}	2021.9	337.015	338.53	337.55	337.925	338.467
	I_{sc}	4.790	28.741	22.460	27.292	27.270	23.895
Uniform	V_{oc}	2066.3	344.382	344.38	344.382	344.382	344.382
	I_{sc}	4.793	28.759	28.759	28.759	28.759	28.759

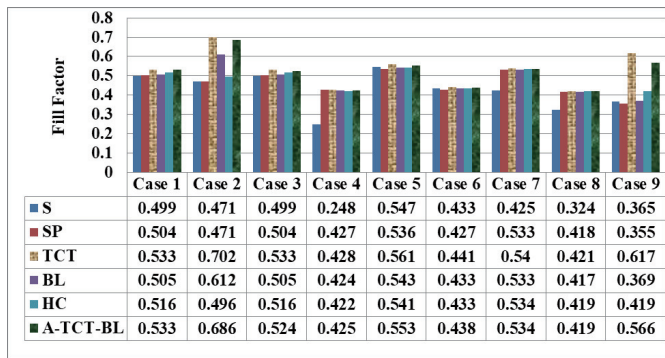


Fig. 20. Fill factor values of PV Configuration for different shading patterns.

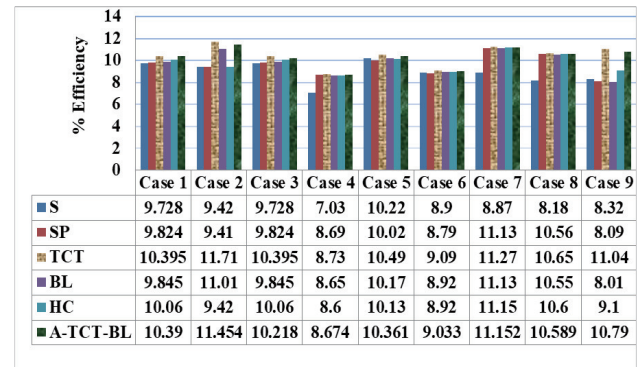


Fig. 21. Efficiency of PV Configuration for different shading patterns.

the TCT PV Configuration shows maximum Fill Factor for all PSCs compared to other PV Configurations. This is also seen graphically in Fig. 20. Fill factor is 0.726 under a uniform insolation condition for all PV Configurations. It is also worth mentioning that A-TCT-BL PV Configuration also generates Fill Factor values very close to TCT. In case 1, TCT and A-TCT-BL PV Configuration's fill factor values are the same.

F. Efficiency of PV Array Configuration

Table in Fig. 21 indicates the values of efficiency of PV array Configuration for all PSCs for various PV Configurations. It is found that the TCT PV Configuration shows maximum efficiency for all PSCs compared to other PV Configurations. This is also seen graphically in Fig. 21. It is also to be noted that A-TCT-BL PV Configuration produces efficiency higher than S, SP, BL and HC under most of the PSCs. Also its values are very close to the TCT efficiency values.

VII. COMPARATIVE STUDY

The maximum power generated under uniform irradiance by the S, SP, TCT, BL, HC and A-TCT-BL PV Configurations are 7199.6 W. Under PSCs it is seen that the shading loss remains the same for all PV Configurations for a particular

shading pattern. The shading loss is minimum in case 5 and is equal to 1018.049 W for all PV configurations.

The total numbers of cross ties in the 6×6 TCT PV Configuration are 25. There are 12 cross ties in the 6×6 BL, 13 cross ties in the 6×6 HC and 19 cross ties in the 6×6 A-TCT-BL PV Configuration. The TCT PV Configuration generates GMPP of 5227.7 W in case 1 (central shading), 5734.7 W in case 2 (diagonal), 5227.7 W in case 3 (corner), 2953.3 W in case 4 (L-shaped), 5511.9 W in case 5 (short and narrow), 4310.6 W in case 6 (short and wide), 5269.1 W in case 7 (long and narrow), 4072.7 W in case 8 (long and wide) and 4692 W in case 9 (random).

These GMPP values are higher than the S, SP, BL, HC and A-TCT-BL PV Configurations for all the nine shading patterns considered, which are shown in Fig. 18. The GMPP value of the A-TCT-BL PV Configuration is 5225.23 W for case 1, which is very close to the GMPP generated by TCT. The other GMPP values of A-TCT-BL are 5604.7 W for case 2, 5138.7 W for case 3, 2933 W for case 4, 5439.55 W for case 5, 4282.1 W for case 6, 5210.56 W for case 7, 4048.2 W for case 8 and 4583.3 W for case 9. All these values are higher than the GMPP produced by the S, SP, BL and HC PV Configurations, except in case 4 where the GMPP of SP and

in case 7 and case 8 where the GMPP of HC is higher than the A-TCT-BL PV Configuration.

Mismatching Losses of the TCT PV Configuration are 11.84, 0.58, 11.84, 25.85, 10.83, 22.80, 4.24, 9.63 and 6.18% for case 1 to 9 respectively which are less when compared to other PV Configurations considered as shown in Fig. 19.

Whereas mismatching losses of A-TCT-BL are 11.89, 2.83, 13.34, 26.36, 12, 23.314, 5.311, 10.17 and 8.357% for case 1 to 9 respectively, which are lesser than the S, SP, BL and HC PV Configurations with the exception of case 4 (L-shaped), case 7 (long and narrow) and case 8 (long and wide).

The Fill Factor values of the TCT PV Configurations, namely 0.533, 0.702, 0.533, 0.428, 0.561, 0.441, 0.540, 0.421 and 0.617 under all nine PSCs are higher when compared to other PV Configurations under consideration as shown in Fig. 20. The Fill Factor values of the A-TCT-BL PV Configurations are 0.533, 0.686, 0.524, 0.425, 0.553, 0.438, 0.534, 0.419 and 0.566 for case 1 to 9 respectively which are all greater than the S, SP, BL and HC PV Configurations, with the exception of case 4 where SP generates a higher fill factor than A-TCT-BL.

Lastly, the TCT PV Configuration array efficiency under PSCs is the highest, namely 10.91, 11.71, 10.91, 8.73, 10.49, 9.09, 11.27, 10.65 and 11.04% respectively for all nine PSCs. The A-TCT-BL PV Configuration shows the second highest efficiency under all 9 PSCs, namely 10.390, 11.454, 10.218, 8.674, 10.361, 9.033, 11.152, 10.589 and 10.790% with the exception of case 8, where HC generates a higher efficiency than the A-TCT-BL PV Configuration.

VIII. CONCLUSION

This research paper has analysed the performance of the S, SP, TCT, BL, HC and A-TCT-BL PV Configurations to extract maximum power under uniform irradiance conditions and with PSCs, such as center, diagonal, corner, L-shaped, short and narrow, short and wide, long and narrow, long and wide and random shading. The PV Configurations are compared on the basis of open circuit voltage, short circuit current, maximum voltage, maximum current, GMPP, shading loss, mismatching loss, fill factor and efficiency. It was determined that maximum power generated under PSCs is less than the uniform irradiance condition. Multiple peaks of power are produced due to PSCs. It was observed that the TCT PV Configuration generates maximum power under all nine PSCs considered. Mismatching loss is substantially minimized in the TCT PV Configuration owing to a greater number of cross ties in the Configuration.

It is observed that the A-TCT-BL PV Configuration generates high values of GMPP compared to the S, SP, BL and HC PV Configurations for most of the PSCs considered. It has also minimized the mismatching losses compared to the S, SP, BL and HC PV Configurations for most of the PSCs considered; the Fill factor and efficiency of the TCT PV Configuration is higher compared to all other PV Configurations considered. The A-TCT-BL PV Configuration also has proved to generate a higher fill factor and efficiency compared to the S, SP, BL and HC PV Configurations for most of the PSCs considered.

The TCT PV Configuration proves to be the obvious choice for any shading pattern under consideration. However owing to more wiring complexities and increased cost of wiring in the case of the TCT PV Configuration; the A-TCT-BL PV Configuration can be considered as the next best choice for a grid-connected PV system. With a lesser number of cross ties, and lesser wiring complexities but generating maximum power by mitigating mismatching power losses, the A-TCT-BL PV Configuration can serve as the second excellent choice after the TCT PV Configuration.

APPENDIX

TABLE AI
PARAMETERS OF CANADIAN SOLAR CS5P-200 M PV MODULE

No	Module Parameters	Values
1.	Maximum Power (P_{max})	199.984 W
2.	Open Circuit Voltage (V_{oc})	57.4 V
3.	Maximum Voltage (V_m)	46.4 V
4.	Short Circuit Current (I_{sc})	4.78 A
5.	Maximum Current (I_m)	4.31 A
6.	Number of cells per module (N_s)	96
7.	Series resistance (R_s)	0.87919 Ω
8.	Shunt resistance (R_{sh})	194.929 Ω
9.	Diode ideality factor (A)	0.98843
10.	Diode Saturation Current (I_o)	2.6826×10^{-10} A
11.	Temperature co-efficient of open circuit voltage (K_v)	-0.37401%/deg.C
12.	Temperature co-efficient of short circuit current (K_i)	0.088996%/deg.C
13.	Dimensions of the PV module	63.1 $\times$ 41.8 inches

REFERENCES

- [1] O. Bingöl and B. Özkaya, "Analysis and comparison of different PV array configurations under partial shading conditions," *Solar Energy*, vol. 160, pp. 336–343, Jan. 2018.
- [2] W. Jaideaw, A. Suksri, and T. Wongwuttanasatian, "Simulation of photovoltaic module configuration for different shaded patterns," *IOP Conference Series: Earth and Environmental Science*, vol. 113, pp. 012204, Feb. 2018.
- [3] F. Belhachat and C. Larbes, "Modeling, analysis and comparison of solar photovoltaic array configurations under partial shading conditions," *Solar Energy*, vol. 120, pp. 399–418, Oct. 2015.
- [4] M. Z. Ramli and Z. Salam, "Analysis and experimental validation of partial shading mitigation in photovoltaic system using integrated dc-dc converter with maximum power point tracker," *IET Renewable Power Generation*, vol. 13, no. 13, pp. 2356–2366, Jul. 2019.
- [5] S. Bana and R. P. Saini, "Experimental investigation on power output of different photovoltaic array configurations under uniform and partial shading scenarios," *Energy*, vol. 127, pp. 438–453, May 2017.
- [6] S. Mohammadnejad, A. Khalafi, and S. M. Ahmadi, "Mathematical analysis of total- cross-Tied photovoltaic array under partial shading condition and its comparison with other configurations," *Solar Energy*, vol. 133, pp. 501–511, Aug. 2016.
- [7] H. Patel and V. Agarwal, "MATLAB-based modeling to study the effects of partial shading on PV array characteristics," *IEEE transactions on Energy Conversion*, vol. 23, no. 1, pp. 302–310, Mar. 2008.
- [8] N. D. Kaushika and N. K. Gautam, "Energy yield simulations of inter-connected solar PV arrays," *IEEE Transactions on Energy Conversion*, vol. 18, no. 1, pp. 127–134, Mar. 2003.
- [9] R. Ramaprabha and B. L. Mathur, "A comprehensive review and analysis of solar photovoltaic array configurations under partial shaded conditions," *International Journal of Photoenergy*, vol. 2012, pp. 120214, Mar. 2012.
- [10] Y. J. Wang and P. C. Hsu, "Analytical modelling of partial shading and different orientation of photovoltaic modules," *IET Renewable Power Generation*, vol. 4, No. 3, pp. 272–282, May 2010.
- [11] Y. J. Wang and P. C. Hsu, "An investigation on partial shading of PV modules with different connection configurations of PV cells," *Energy*, vol. 36, no. 5, pp. 3069–3078, May 2011.

- [12] M. Dhimish, V. Holmes, B. Mehrdadi, M. Dales, B. Chong, and L. Zhang, "Seven indicators variations for multiple PV array configurations under partial shading and faulty PV conditions," *Renewable Energy*, vol. 113, pp. 438–460, Dec. 2017.
- [13] P. R. Satpathy, S. Jena, and R. Sharma, "Power enhancement from partially shaded modules of solar PV arrays through various interconnections among modules," *Energy*, vol. 144, pp. 839–850, Feb. 2018.
- [14] V. Jha and U. S. Triar, "A detailed comparative analysis of different photovoltaic array configurations under partial shading conditions," *International transactions on Electrical Energy Systems*, vol. 29, No. 6, pp. e12020, Jun. 2019.
- [15] J. D. Bastidas-Rodríguez, L. A. Trejos-Grisales, D. González-Montoya, C. A. Ramos-Paja, G. Petrone, and G. Spagnuolo, "General modeling procedure for photovoltaic arrays," *Electric Power Systems Research*, vol. 155, pp. 67–79, Feb. 2018.
- [16] M. Z. Shams El-Dein, M. Kazerani, and M. M. A. Salama, "Optimal photovoltaic array reconfiguration to reduce partial shading losses," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 145–153, Jan. 2013.
- [17] G. Sai Krishna and T. Moger, "Reconfiguration strategies for reducing partial shading effects in photovoltaic arrays: State of the art," *Solar Energy*, vol. 182, pp. 429–452, Apr. 2019.
- [18] V. M. Ram Tatabhatla, A. Agarwal, and T. Kanumuri, "Performance enhancement by shade dispersion of Solar Photo-Voltaic array under continuous dynamic partial shading conditions," *Journal of Cleaner Production*, vol. 213, pp. 462–479, Mar. 2019.
- [19] G. Walker, "Evaluating MPPT converter topologies using a MATLAB PV model," *Journal of Electrical & Electronics Engineering*, vol. 21, No. 1, pp. 49–55, Jan. 2001.
- [20] W. De Soto, S. A. Klein, and W. A. Beckman, "Improvement and validation of a model for photovoltaic array performance," *Solar Energy*, vol. 80, no. 1, pp. 78–88, Jan. 2006.
- [21] S. Shongwe and M. Hanif, "Comparative Analysis of Different Single-Diode PV Modeling Methods," *IEEE Journal of Photovoltaics*, vol. 5, No. 3, pp. 938–946, May 2015.
- [22] S. Motahhir, A. El Ghzizal, S. Sebti, and A. Derouich, "Modeling of photovoltaic system with modified incremental conductance algorithm for fast changes of irradiance," *International Journal of Photoenergy*, vol. 2018, pp. 3286479, Mar. 2018.
- [23] S. R. Pendem and S. Mikkili, "Modelling and performance assessment of PV array topologies under partial shading conditions to mitigate the mismatching power losses," *Solar Energy*, vol. 160, pp. 303–321, Jan. 2018.
- [24] S. Malathy and R. Ramaprabha, "Comprehensive analysis on the role of array size and configuration on energy yield of photovoltaic systems under shaded conditions," *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 672–679, Sep. 2015.
- [25] A. S. Yadav, R. K. Pachauri, Y. K. Chauhan, S. Choudhury, and R. Singh, "Performance enhancement of partially shaded PV array using novel shade dispersion effect on magic-square puzzle configuration," *Solar Energy*, vol. 144, pp. 780–797, Mar. 2017.
- [26] R. Ahmad, A. F. Murtaza, H. A. Sher, U. T. Shami, and S. Olalekan, "An analytical approach to study partial shading effects on PV array supported by literature," *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 721–732, Jul. 2017.



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