Effect of Partial Shading and Performance Analysis on Various Array Configurations of Photovoltaic System

Aidha Muhammad Ajmal
Institute of Power Engineering
Universiti Tenaga National
Kajang, Selangor, Malaysia
aida_khan_1@yahoo.com

Sudhakar Babu Thanikanti
Institute of Power Engineering
Universiti Tenaga National
Kajang, Selangor, Malaysia
sudhakarbabu66@gmail.com

Vigna Kumaran Ramachandaramurthy
Institute of Power Engineering
Universiti Tenaga National
Kajang, Selangor, Malaysia
Vigna@uniten.edu.my

Janaka Ekanayake
Institute of Power Engineering
Universiti Tenaga National
Kajang, Selangor, Malaysia
jbe@ee.pdn.ac.lk

Mohd Tariq
Department Of Electrical Engineering
ZHCET,
Aligarh Muslim University
Aligarh, India
tariq.ee@zhcet.ac.in

***Abstract*—Non-uniform irradiations or shading conditions affect the output power of photovoltaic array, by causing multiple peaks in its characteristics. To overcome this limitation, several photovoltaic array configurations have been proposed in literature such as Series-Parallel (SP), Total-Cross-Tied (TCT) and Bridge-Linked (BL). In this paper, these three array configuration techniques are simulated for an 11kV, 1 MWph PV plant using MATLAB/SIMULINK. Comparative studies for three methods are performed in-terms of power loss, mismatch loss and fill factor under various shade condition. Simulation results show that the TCT configuration generates 56 kW and 100 kW power more than SP and BL respectively for case 1. In case 2, TCT generates additional 54 kW and 46 kW than SP and BL while in case 3, TCT generates additional 4 kW and 17 kW than SP and BL respectively. Simulation results and comparative study confirm that the Total-Cross-Tied configuration has excellent performance and generates more power under wide range of partial shading conditions than Series-Parallel and Bridge-linked configurations.**

Keywords—partial shading, photovoltaic, series-parallel, total-cross-tied, bridge-linked

I. Introduction

Green energy sources have become alternative to fossil fuel due to the increasing demand of global energy. Solar Photovoltaic (PV) system is one of the popular alternative sources to generate electricity to meet the required energy demand. However, the PV has limitations due to non-linear characteristics and its performance greatly depends on the environmental conditions like irradiation and temperature [1, 2]. In addition, all PV panels in a plant may not receive equal amount of irradiation due to building shadows, trees, snow, passing clouds, dust and bird dropping [3]. During these conditions, the less irradiated PV modules act as a load, thereby increasing the temperature inside the panel and causing hot spots which damage the PV module. This can be overcome by connecting bypass diode across each module. However, the power generating capacity and overall efficiency of PV plant reduces [4]. To enhance its power generating capacity, maximum power extracting techniques have evolved. The maximum power extraction can be done using different methods namely, 1) Maximum Power Point Tracking (MPPT) algorithms with the help of power electronics converter or inverter [5, 6], 2) Distributed MPPT techniques [7] and 3) Array reconfiguration [2, 8]. Among these methods, array reconfiguration has gained the highest interest as it does not involve power electronic inverter/converters, has fewer losses and achieves high efficiency than other methods [9, 10]. Many researchers have worked on different reconfiguration techniques and proved the enhancement of PV power generation [3, 11]. Authors in [12, 13] provided a solution for partial shading by using multilevel inverter with independent voltage controller to achieve the MPPT of each PV module. While in [14], a parallel configuration of PV array is suggested to prevent the shading losses. However, the technique presented in [14] requires additional switches and sensors that lead the system to become more complex besides increasing the cost. In [15], 3×3 PV array of SP, TCT and BL configurations have been implemented to evaluate the efficiency of PV array under different shading conditions. While in [16], 6×4 PV array of series, parallel, SP, TCT and BL configurations have been analysed and the performance of various configurations are compared under different shading patterns using Bishop model of PV modules. Different sizes of PV array have been tested and compared under different cases of shading conditions for series, parallel, SP, TCT and BL configurations in [17]. The results from [15-17] show the preference of the TCT configuration over series, parallel, SP, TCT and BL configurations. In [18, 19] and in [20], 5×5 and 6×6 PV array of Series, SP, TCT, BL and Honey-Comb (HC) configurations have been simulated using MATLAB/SIMULINK under various shading conditions. The simulated results of MPP for different configurations have been compared. From the literature, it is observed that most of the authors presented their methods with small size of PV array and the performance analysis and real time implementation in a MW plant are not considered.

In this article, authors made an attempt to test the power generating capacity of SP, TC and BL configurations under a wide range of partial shading conditions for a 1 MWpk plant. In addition to estimate the superiority of these configurations, mismatch loss, fill-factor (FF) and power losses were also evaluated. From the results presented, it confirms that TCT configuration exhibit superior performance and generates more power under various shading conditions than other configurations.

II. Modelling of Photovoltaic Cell

The PV array comprises of a number of PV modules in series and parallel, to meet the required power. Each PV

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module is developed by interconnecting a number of series and parallel PV cells. The equivalent circuit of a PV cell is shown in Fig. 1.

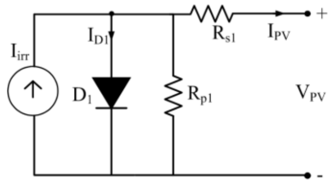


Fig. 1. Equivalent Circuit Diagram of PV cell.

The ideal PV cell includes a current source, I_{irr} and diode, D_1. The total current generated by PV cell I_{PV} can be given as shown in Equation (1) [21].

$$I_{PV} = I_{irr} - I_0\left\{\exp\left(\frac{q(V_{PV} + R_{S1}I_{PV})}{A_1 k_b T}\right) - 1\right\} - \frac{V_{PV} + R_{S1}I_{PV}}{P_{P1}} \quad (1)$$

where, R_{s1} and R_{p1} are the series and parallel resistance respectively, A_1 is the ideality factor, k_b is the Boltzmann's constant equivalent to 1.3806×10^{-23} J/K, T is temperature in Kelvin, q is the electron charge (1.60217×10^{-19} Column), I_0 is the saturation current, I_{D1} is the diode current, I_{PV} and V_{PV} are the output current and voltage of photovoltaic cell. The diode current I_{D1} can be expressed as in equation (2).

$$I_{D1} = I_0\left\{\exp\left(\frac{q(V_{PV} + R_{S1}I_{PV})}{A_1 k_b T}\right) - 1\right\} \quad (2)$$

III. Configuration of PV Array and Grid Connected System

This section discusses the structure of 5×5 PV modules connected in SP, TCT and BL configuration. The configurations are shown in Fig. 2. In SP configuration, PV modules are connected in series and then connected in parallel. For TCT configuration, the SP connection is enhanced by having crosstie between the modules in each row. For BL configuration, modules are connected as a bridge and this configuration is in between SP and TCT.

A. Grid connected PV array

Fig. 3 shows the block diagram of the proposed system, in which PV array of 1 MWpk is connected to the grid through a DC/AC inverter. This PV array is designed in such a way that the configuration of PV array can be changed from one configuration to another. For the PV system, PV module of MYS-60P-B3-CF-245 type is used and its specifications are presented in Table 1. The PV system is designed to achieve maximum power of 1 MWpk under standard test conditions (STC). However, the power generation is mainly dependent on the environmental conditions like irradiation, temperature and partial shading. The DC current, (I_{PV}) and DC voltage, (V_{PV}) generated from the PV array are converted to AC current, (I_{AC}) and AC voltage, (V_{AC}) using DC/AC inverter.

IV. Results and Discussion

The 1 MWpk system presented in Fig. 3 is developed using SP, TCT and BL configuration in MATLAB/SIMULINK. These configurations were tested under three different partial shading conditions as shown in Fig. 4. In each case, PV array configurations is subjected to different irradiation levels such as 200 W/m^2, 500 W/m^2, 800 W/m^2 and 1000 W/m^2 and are made to occur at different position for each case. The system is operated under constant temperature of 298.15 Kelvin. The three different shading cases are described in the following section. The PV modules which are used to construct a 1 MWpk system are sub-grouped and the final configuration of the system is made into 6×15 PV array structure.

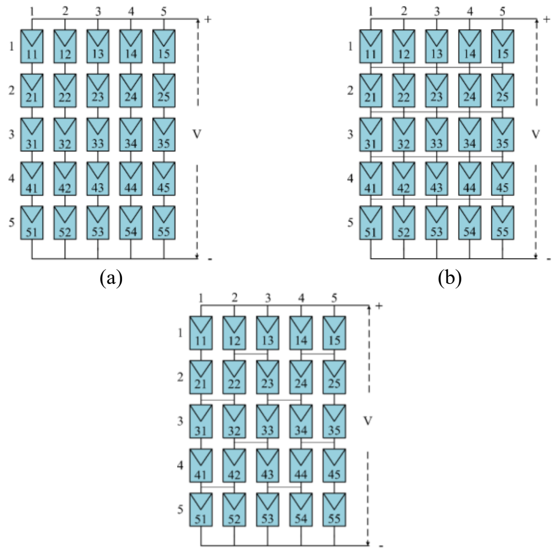


Fig. 2. 5×5 PV array configurations, (a) SP configuration, (b) TCT configuration, (c) BL configuration.

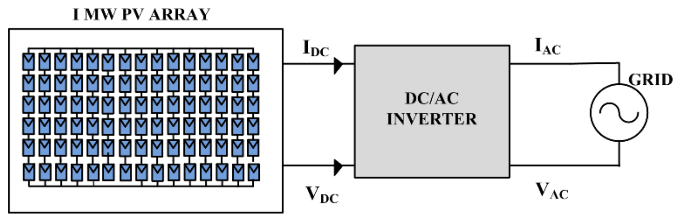


Fig. 3. Grid Connected PV Array.

TABLE 1 MYS-60P-B3-CF-245

Parameter	Datasheet value
Rated power	245.2 W
Open circuit voltage (V_{OC})	37.26 V
Short circuit current (I_{SC})	8.35 A
Voltage at maximum power (V_{mp})	30.96 V
Current at maximum power (I_{mp})	7.92 A
Number of cell in series (N_s)	60
Number of cell in parallel (N_p)	1

For **Case 1**, the shading is imposed in the middle of the PV array as shown in Fig. 4a. In this case, six modules are under 200 W/m^2, five nodules under 500 W/m^2, eight modules under 800 W/m^2 while all other modules are under full irradiations of 1000 W/m^2.

The respective P-V, an I-V curve which reflects the impact of partial shading and the power generation under case 1 for SP, BL and TCT are presented in Fig. 5(a), 5(b). In addition, the total generated DC power and AC power transmitted to grid are presented in Fig. 5(c), 5(d). From Fig. 5(a), it can be observed that, SP, BL, TCT configurations generates 805 kW, 770 kW, 870 kW respectively. Further, it is observed that the SP configuration involves more number of multiple peaks in the P-V curves. From the P-V curves, it can be confirmed that TCT configuration generates 870 kW as compared to SP and BL configurations. To verify the total DC generated power and amount of AC power transmitted to grid, dynamic test is performed over three configurations. During the dynamic time from 0 to 1.5 sec, all the modules of PV array receive full irradiation. During this time, the generated power at DC side and AC side are almost equal for all three different configurations. At 1.5 sec, partial shading conditions are applied over the PV array until 3.5 sec. During this time the DC and AC power generated starts to decrease. After 3.5 sec, the generated power at DC side and AC side starts to increase again when the partial shading conditions are removed and all the modules receive full irradiation level, for the three different configurations. Fig. 5(c), 5(d) confirms that the total DC generated power and AC power transmitted to grid for TCT configuration is higher than the SP and BL configurations during partial shading conditions.

For **Case 2**, shading is applied in such a way that the top-right side of PV array where, six modules are subject to 200 W/m^2, six modules under 500 W/m^2, eight modules under 800 W/m^2 and other modules under fully irradiation, as shown in Fig. 4(b).

Fig. 4. Photovoltaic Array under Partial Shading Condition, (a) Case 1, (b) Case 2 (c) Case 3.

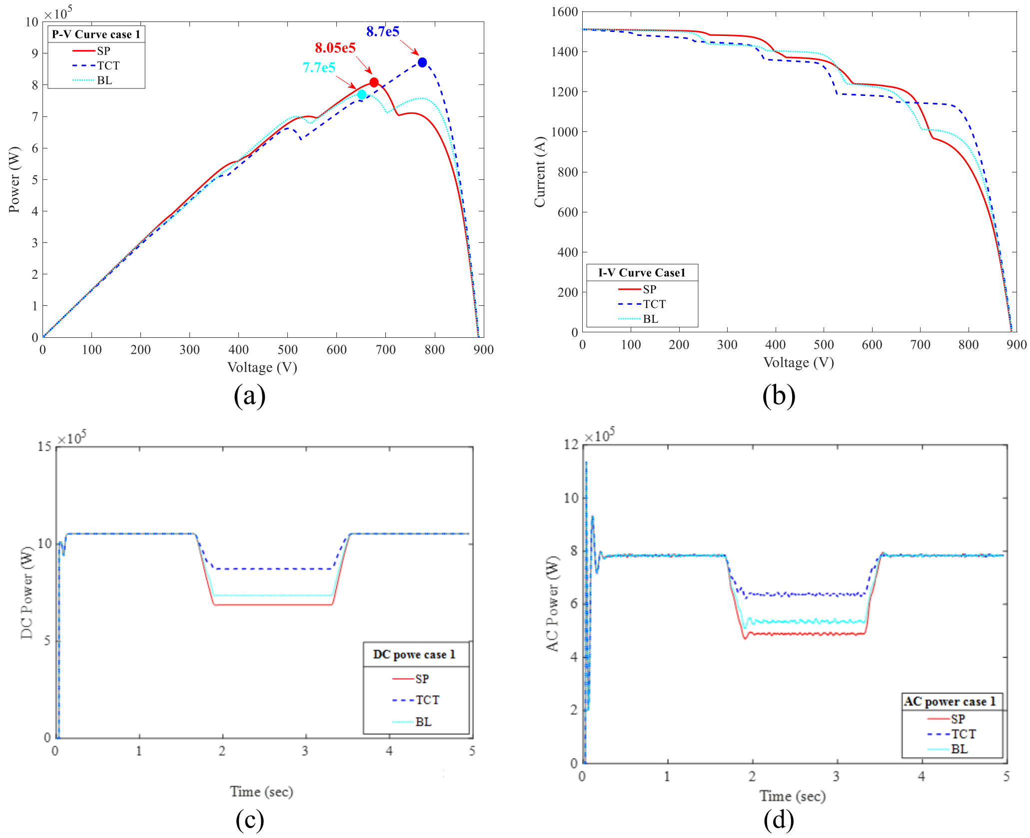


Fig. 5. Performance of SP, BL and TCT under case 1, (a) P-V curve, (b) I-V curve, (c) DC power, (d) AC power.

The P-V, and I-V curve under case 2 for SP, BL and TCT are presented in Fig. 6(a) and 6(b). From Fig. 6(a), it can be observed that the TCT configurations generates the highest maximum power of 907 kW, followed by BL configuration at 861 kW and the SP configuration presents the lowest power generated at 853 kW. For the dynamic test, partial shading is made to occur at 1.5 sec to 3.5 sec. Expect this duration three configurations generates and transmitted almost equal amount of power. During the partial shading time from 1.5 sec to 3.5 sec, the power generation will be reduced. The total generated DC power and AC power transmitted to Grid are presented in Fig. 6(c), 6(d). From Fig. 6(c) and 6(d), it can be observed that TCT configuration generates the highest DC power of 900 kW and AC power of 660 kW during partial shading condition. However, the SP and BL configurations generate almost the same DC power 860 kW and AC power 630 kW.

In **Case 3**, partial shading occurs at the bottom-left side of PV array. In this case, nine modules receive 200 W/m^2, five modules under 500 W/m^2, six modules under 800 W/m^2 and others under full irradiation of 1000 W/m^2, as presented in Fig. 4(c).

The P-V and I-V curve under case 3 for SP, BL and TCT are presented in Fig. 7(a), 7(b). In this case, TCT configuration delivers the highest maximum power at 740 kW, followed by SP configuration at 736 kW and the lowest power generated by BL configuration at 723 kW as presented Fig. 7(a). From the P-V curves it can be confirmed that TCT configuration generates higher power than SP and BL configurations. In case of step variation, the total generated DC power and AC power transmitted to Grid are presented in Fig. 7(c), 7(d). As shown in Fig. 7(c), 7(d), the DC and AC power of TCT configuration are 700 kW and 500 kW respectively during shading period of 1.5 sec to 3.5 sec. The SP and BL configurations generate almost the same DC power of 660 kW and AC power of 480 kW. From the DC power and AC power curves, it can be confirmed that TCT configuration generates higher power than SP and BL configurations.

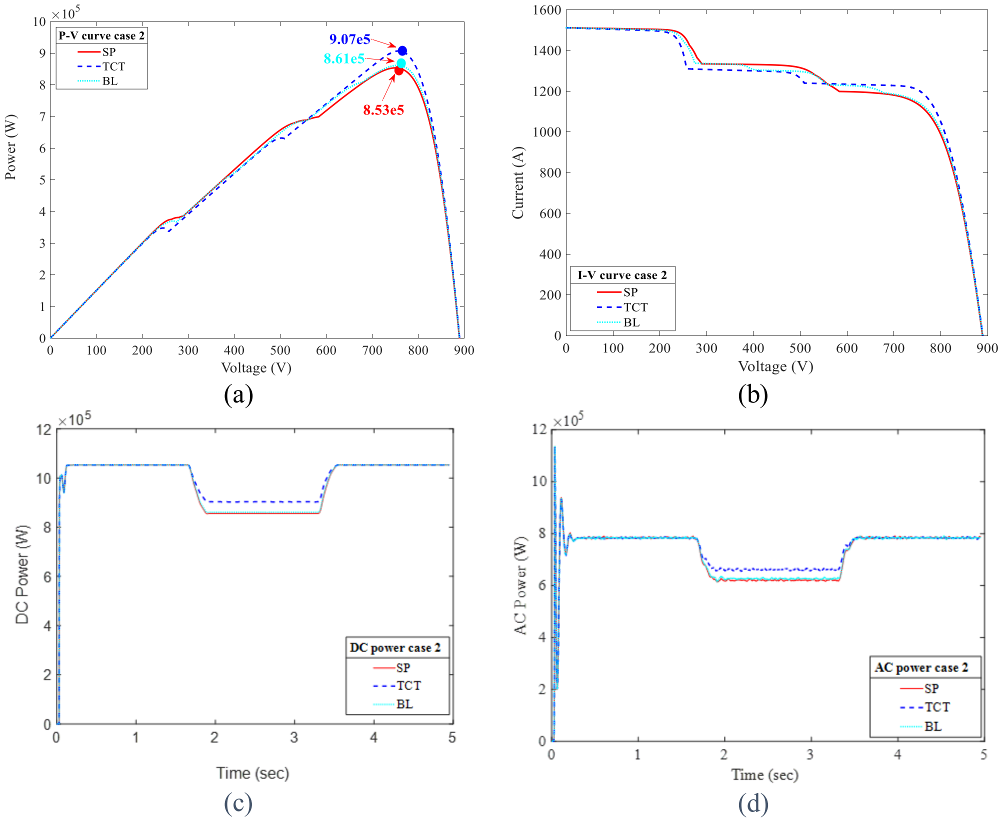
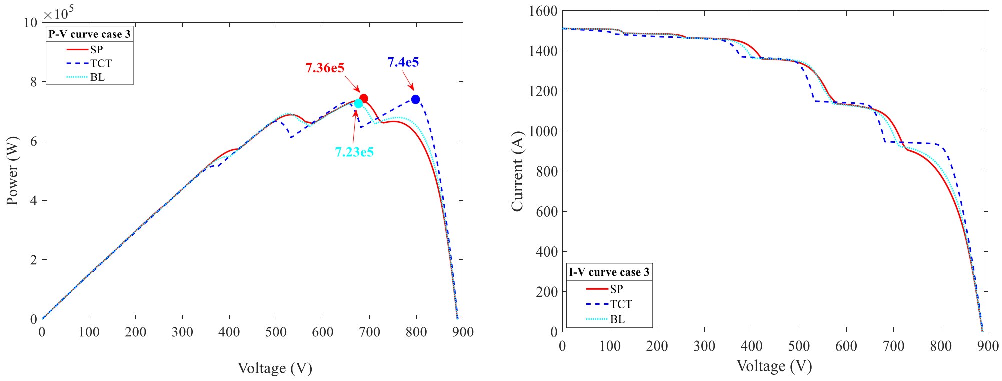
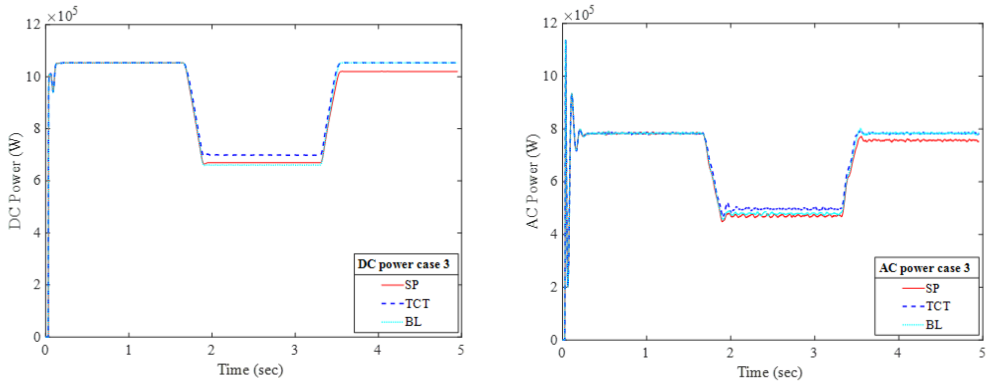


Fig. 6. Performance of SP, BL and TCT under case 2, (a) P-V curve, (b) I-V curve, (c) DC power, (d) AC power.



(a) (b)



(c) (d)

Fig. 7. Performance of SP, BL and TCT under case 3, (a) P-V curve, (b) I-V curve, (c) DC power, (d) AC power.

V. Performance Analysis

For comparison of TCT, SP and BL configurations, the following criteria's are employed: (1) mismatch loss, (2) power loss, (3) Fill Factor.

When shading occurs on the modules of PV array, the maximum power point (MPP) of P-V curve does not match with the MPP of P-V curve during non-shading conditions. This leads to reduced power and it is known as mismatch loss. It is one type of the partial shading losses of PV array as shown in Fig. 8. The MPP under uniform irradiation is higher than the MPP under shading conditions. The variance between the power generated caused by shading loss cannot be ignored. For each shading case, the performance values for various configurations are evaluated and compared such as mismatch loss, power loss and fill factor (FF).

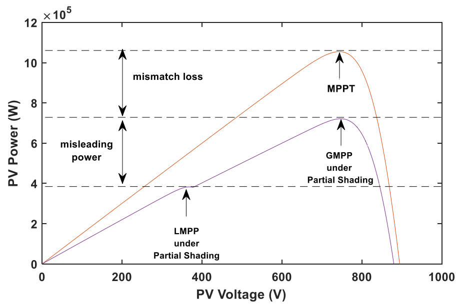


Fig. 8. Partial Shading Losses.

A. Mismatch losses

The mismatch losses can be calculated by using the equation(3)

$$P_{mismatch-loss} = P_{MPPT} - P_{GMPP} \quad (3)$$

The mismatch loss is defined by the difference between the Maximum Power Point during uniform irradiations, P_{MPPT} and the power at Global Maximum Power Point, P_{GMPP} during shading conditions as shown in equation (3). This leads to reduction of the generated power from PV array. Fig. 9 presents the mismatch loss values of PV array for various configurations under the three different shaded conditions, the SP and BL configurations have the higher values in the bar diagram whereas, the TCT configuration has less value in mismatch power loss as shown in Fig. 9. Hence, the performance of the TCT configuration is best compared with SP and BL configurations under different shading condition.

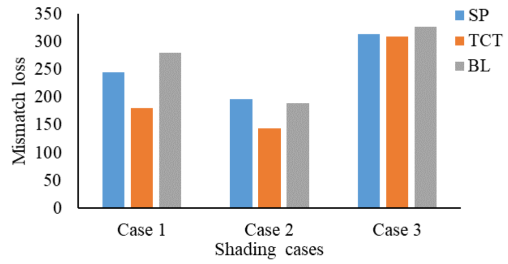


Fig. 9. Mismatch loss of PV array during various shade cases.

B. Power loss

Power Loss (ΔP_{loss}) it is determined as the ratio of difference between Maximum Power Point Tracking (P_{MPPT}) of PV array at STC and the Global Maximum Power Point (P_{GMPP}) of the PV array under shading condition. The equation representing power loss is given in equation (4). It can be represented in %.

$$\Delta P_{loss} = \frac{P_{MPPT} - P_{GMPP}}{P_{MPPT}} \times 100 \quad (4)$$

Fig 10 shows the power loss values of SP, TCT and BL configurations during various cases of shading conditions. As shown in Fig. 10, the power loss of TCT configuration is 17.14 % in case 1, 13.62 % in case 2 and 19.52 % in case 3. While the power loss in SP configuration are 23.33 %, 18.76 % and 30 % for case 1, case 2 and case 3 respectively. Finally, in BL configuration the power losses are 26.66 %, 18 % and 31.14 % for case 1, case 2 and case 3 respectively. From Fig. 10, it can be confirmed that TCT configuration has higher performance than SP and BL configurations.

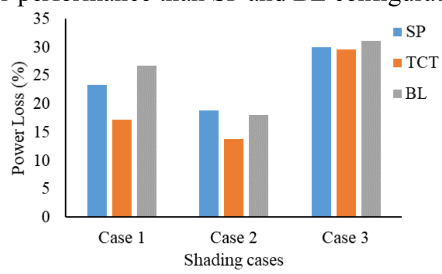


Fig. 10. Power loss of PV array during various shade cases.

C. Fill factor (FF)

The loss in the generated power caused by shading conditions is referred as the Fill Factor (FF) and is determined by equation (5).

$$FF = \frac{P_{GMPP}}{V_{O.C} \times I_{S.C}} \times 100 \quad (5)$$

Fill factor (FF) of PV array caused by shading effects and it depends on a short circuit current, I_{SC} open circuit voltage, V_{OC} and P_{GMPP} as equation (5), increasing in the shading that occurs on the photovoltaic array the FF will decrease. Fig. 11 shows the evaluation FF of SP configuration, TCT configuration and BL configuration, during shading conditions. The Fill Factor is calculated for three cases which are discusses in previous section. The value of FF attainted by TCT configuration shown in Fig. 11 has the higher FF for all cases of shading conditions compared to other configurations SP and BL, as FF increase the losses will decrease, hence, the TCT configuration has the most power generation and best performance compared with SP and BL configurations.

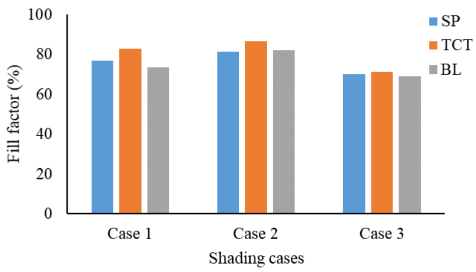


Fig. 11. Fill factor of PV array during various shade cases.

CONCLUSION

In this paper, three different PV configurations of series-parallel, total-cross-tied and bridge-linked are tested under three different partial shading conditions. For estimating the superiority among these methods, performance indicators like mismatch loss, power loss and fill factor also evaluated for three cases. From the presented I-V, P-V curves and performance indicators, it is noteworthy to mention that the TCT configuration has higher performance and generated more power under all shading conditions. Also, the results show more power loss in SP and BL configurations compared with TCT configuration. The results of TCT configuration under partial shading conditions are the best and suitable to improve the efficiency and the behavior of PV array for this configuration, by new technologies like artificial intelligence technique (AI) to generate more power and reduce the power losses under shading conditions in future.

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