Comparative Study on Solar Photovoltaic Array Configurations Under Irregular Irradiance Conditions

Sai Krishna G.* and Tukaram Moger
Department of Electrical & Electronics Engineering
National Institute of Technology Karnataka, Surathkal, INDIA.
*Email: saikrishna240@gmail.com

***Abstract*—Power delivered by a Photovoltaic (PV) cell decreases significantly due to non-uniform irradiance condition. Consequently, in case of PV module or array, the generated output power get reduces and further deteriorates the overall system performance. Many solutions have been reported to reduce partial shadings. Among all, PV array configurations is the effective solution for this problem. Various PV array configurations are mentioned in the literature to mitigate partial shading condition (PSC). This paper presents the comparative study on PV array configurations reported in the literature such as "Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Link (BL), Honey-Comb (HC), Modified Bridge-Link (MB), hybrid SP-TCT, hybrid BL-TCT along with proposed hybrid HC-TCT" under partial shading conditions on 4×4 PV array. Further, the performances of all configurations are investigated by comparing the global maximum power point (GMPP), voltage at the global maximum power (V_{GMPP}), fill-factor (FF) and possible local peaks (PLP) by using MATLAB-SIMULINK.**
***Key words* : PV Modelling, Partial shading condition (PSC), PV array configurations.**

NOMENCLATURE

$V_{cell/pv/a}$	: PV cell/module/array voltage (V)
$I_{cell/pv/a}$	: PV cell/module/array current(A)
I_d	: diode current
I_{sh}	: Shunt current
T_c	: PV module operating temperature
T_{STC}	: Standard operating temperature at $298.15K$
I_{do}	: Reverse saturation current in STC
n	: Ideality factor
k	: Boltzmann's constant 1.3805×10^{-23}J/K
q	: Electron charge 1.6×10^{-19}C
G	: Actual Irradiance of PV module
R_s, R_{sh}	: Parasitic resistance of a PV module
n_s	: No.of solar cells connected in series
G_{STC}	: Standard PV irradiance at 1000 W/m^2

I. INTRODUCTION

The utilization of electrical energy is increasing day by day worldwide[1]. In general, the energy basically in the form of conventional and non-conventional sources or renewable energy resources (RES). Conventional sources are coal, oil and fossil fuels. The use of conventional energies causes environmental degradation due to effect of pollution and organic chemical reactions, thus increasing the need for use of renewable energies, which are solar, wind, biogas and geothermal, etc. Among all, the solar energy is the most essential and prerequisite sustainable resource because of its ubiquity and abundance in nature [1]-[2]. In short time, the PV energy is gaining more attention from the consumers due to its following advantages; fuel free, less maintenance and pollution free. The PV output power is mainly depends on the solar irradiance (G) and ambient temperature (T). These two parameters decide the maximum power point (MPP) of a PV module. Partial shading is one of the main reason to reduce efficiency of the modules. Partial shading condition (PSC), generally occurs when PV modules gets shaded by tree, passing clouds, near buildings, etc,. Under this condition, the shaded module receiving less solar irradinace as compared to unshaded modules, thus creates hot-spot problems in PV array. Further, it may lead to damage of cell or module. To overcome this, a bypass diode is connected across the PV modules in order to protect from the damage [3]. Due to insertion of bypass diodes which exhibits multiple steps in I-V and multiple peaks in P-V curve of the PV array. In the literature many solutions have been reported to mitigate partial shadings [4]. One of the foremost solutions is PV array configurations.

In the literature, different PV array configurations are reported to reduce PSCs. These are "Simple-Series (SS), Parallel (P), Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Link (BL), and Honey-Comb (HC)" [5]. In [4], the authors have developed the mathematical formulation for optimum TCT problem. This problem can be solved by using branch bound (BB) algorithm in order reduce mismatch losses. Later, in [6], the authors have proposed optimal reconfiguration approach for shifting the shaded module locations, thereby minimizing the mismatch index (MI). In [7], the authors have developed new static connection scheme for PV arrays in order to distribute shading effect over the PV array. In [8], the authors have presented comparative study on 6×6 PV array under different PS conditions. In this study, they have considered different types configuration which are "SS, SP, TCT, BL, and HC". The result shows that TCT provides the best performance under all shading patterns. In addition to conventional configurations such as SS, P, SP, TCT, BL and HC, the author in [9] are reported hybrid SP-TCT and hybrid BL-TCT configurations to reduce partial shadings.

This paper presents the comparative study on conventional configurations with hybrid configurations under partial shading conditions. The following configurations are considered for this study: "Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Link (BL), Honey-Comb (HC), Modified Bridge-Link (MB), hybrid SP-TCT, hybrid BL-TCT along with proposed hybrid HC-TCT". Each PV array configuration are studied under different shading conditions on 4×4 PV array and then a comparative analysis is carried out by comparing the various parameters.

This paper is organized as follows: In Section II, different PV array configurations reported in the literature are presented. Section III, presents the mathematical modelling of PV array. In Section IV, result and discussions for PV array configurations under different shading conditions are analysed and then followed by conclusion in SectionV.

II. PV array Configurations

As mentioned in Section I, PV array configurations is one of the effective solutions to reduce the PSCs. Different PV array configurations are reported in the literature, which are "Simple-Series (SS), Parallel, Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Link (BL) and Honey-Comb (HC)". In series configuration, all PV modules are connected in series to improve output voltage. In parallel, all modules are connected in parallel fashion so that the output current will be higher [10]. Under PSCs, the main advantage of parallel over series configuration is that the maximum output power of the parallel configuration is higher than that from the series configuration. The combination of series and parallel connections composes series-parallel configuration as shown in Fig.1(a). This configuration increases both the output voltage and current in at a time. TCT configuration (refer Fig.1(b)), is same as SP configuration but, between the rows tie lines are connected to form junctions. This configuration requires more wires for installation, thus increases the cost of the system. Bridge-link configuration (refer Fig.1(c)) is same as TCT but half of its connections are avoided so that cable losses and wiring installation time are reduced [11]. The combination of both TCT and BL configurations to form HC configuration (refer Fig. 1(d)). The other possible configurations such as Modified-Bridge Link (MB), hybrid SP-TCT and hybrid BL-TCT (refer Fig.2 (e), (f) & (g)) are also reported in the literature [12]-[13]. In addition to this, the hybrid HC-TCT PV array (refer Fig.2(h)) is proposed in this paper.

III. Modelling of Photovoltaic Array

Modelling is the first step for analysing behaviour of the PV system. In fact, good and accurate mathematical models are necessary to achieve operation at optimum point under partial shadings. The modelling of PV array starts with mathematical model of a single PV cell. Several models for solar cell have been reported in the literature. Two of them are one diode PV cell and two diode PV cell models [14]. As it is mentioned in the literature, the two diode solar cell model requires more computational efforts as compared to the one diode model but its output characteristics are very close to the practical behaviour of a PV cell [15]. Hence, many researchers are widely using one diode solar cell model because it is very easy to model as compared to other models. The practical one diode PV cell model is shown in Fig.3. The modelling equations of single diode model are given below:

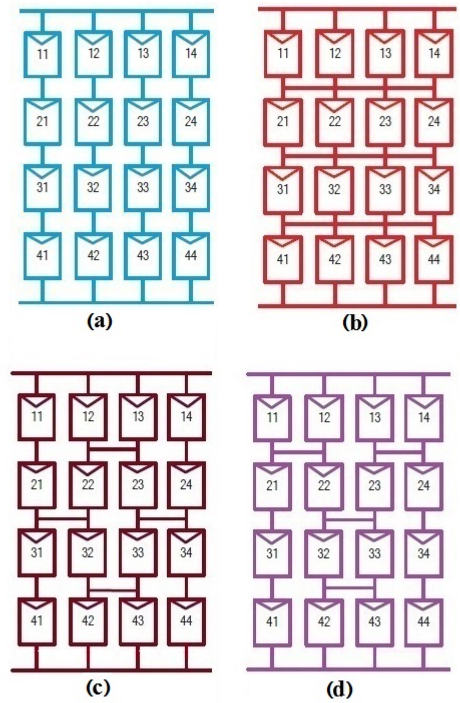

Fig. 1: PV configurations: (a) SP, (b) TCT, (c) BL, (d) HC

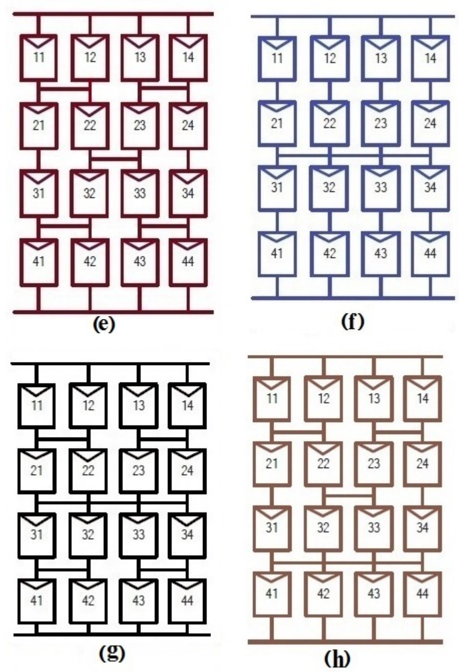

Fig. 2: PV configurations: (e) MB, (f) Hybrid SP-TCT, (g) Hybrid BL-TCT, (h) Hybrid HC-TCT

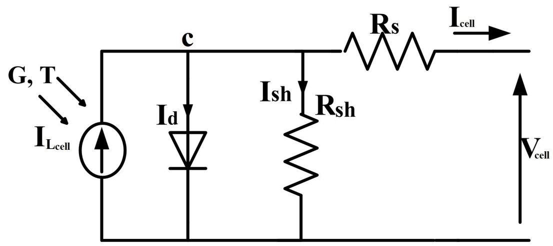

Fig. 3: Practical one diode PV cell model

By applying KCL to node X in Fig.3, I_{pv} can be written as,

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

$$V_T = \frac{KT}{q} \times n \quad (2)$$

The I-V relation of PV cell in ideal condition,

$$I_{cell} = I_{Lcell} - I_o[exp(\frac{V_d}{V_T}) - 1] \quad (3)$$

The reverse-bias saturation current I_o at STC can be written as,

$$I_o = I_{do}[T_c/T_{STC}]^3[Exp(q.E_g/nk)(1/T_{STC} - 1/T_c))] \quad (4)$$

$$I_{cell} = I_{Lcell} - I_o[exp\{\frac{q(V_{cell} + I_{cell}R_s)}{knT} - 1\}] - \frac{(V_{cell} + I_{cell}Rs)}{R_{sh}} \quad (5)$$

The PV module is composed by connecting solar cells in series and adding the parasitic resistance. From Eq.(5), the I-V relation for PV module can be written as,

$$I_{pv} = I_L - I_o[exp\{\frac{q(V_{pv} + I_{pv}R_S)}{n_s knT} - 1\}] - \frac{(V_{pv} + I_{pv}R_S)}{R_{SH}} \quad (6)$$

where R_S and R_{SH} are the series and shunt resistance of the module. It is noticed that Eq.(5) is a transcendental equation and by using Eq.(5), one can find the output current of the PV module. This is not strict with one module, it can also be increased to number of modules connected in series to form string, then all strings are connected to gather and compose PV array. Then, the I-V relation for the PV array is expressed as follows,

$$I_a = N_P.I_L - N_P.I_o exp\{\frac{q(V_a + \frac{N_S}{N_P}I_aR_S)}{N_S knT} - 1\} - (V_a + \frac{N_S}{N_P}I_aR_S)/\frac{N_S}{N_P}R_{SH} \quad (7)$$

where,N_S and N_P is the modules connected in series and parallel. The above equations are used to model PV array with the help of data sheet parameters [9].

A. Description of partial shadings

In this study, different PV array configurations are considered for partial shading analysis. In this study, the PSCs is categorized into three types of shading cases. Each case is considered with two different shading arrangements. In Shading case-I, the shadow movement of the module is increasing vertically upwards covering the first two columns of the PV array as shown in case-I (a), (b) of Fig. 4. In shading case-II, the shadow movement of the module is increasing horizontally moving towards right covering the last two rows of the PV array as shown in case II (a), (b) of Fig. 4. In shading case-III, two different types of shading arrangements are considered, which are shown by case-III (a), (b) of Fig.4. The above mentioned study is carried out at 25^oC temperature and irradiance of shading module is 400 W/m^2. The PV module data sheet parameters are given in [9].

B. Performance parameters

Fill Factor(FF): The fill factor (FF) is essentially measures the area of PV module or array. Which is depends on the open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum power at voltage (V_{mp}) and maximum power at current (I_{mp}). The FF can be determined as,

$$FF = \frac{Power\ at\ GMPP}{V_{oc}.I_{sc}} \quad (8)$$

Possible Local Peaks: In PSCs, each PV array exhibits multiple peaks in P-V characteristics. Among all the multiple peaks, there is only one global peak remaining all are local peaks. The possible local peaks of each PV array configuration is to identify from the observation of output characteristics.

IV. Result and Discussions

In this study, eight PV array configurations are considered, which are "Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Link (BL), Honey-Comb (HC), Modified Bridge-Link (MB), hybrid SP-TCT, hybrid BL-TCT along with proposed hybrid HC-TCT" for study the partial shading effect on 4×4 PV array. The performance analysis is also carried out for configurations by comparing the GMPP, V_{GMPP}, fill factor and possible local peaks. The following studies are performed to investigate the performance of various array configurations under different shading conditions.

- Performance of PV arrays configurations under shading case-I.
- Performance of PV arrays configurations under shading case-II.
- Performance of PV arrays configurations under shading case-III.

A. Performance of PV arrays configurations under shading case-I

The P-V characteristics of PV array configurations for shading case-I are shown in Figs.5-6. In shading case-I (a), the various multiple peaks are observed on the PV curve is shown in Fig.5. From the figure, it is observed that local peaks are very close to the global peaks for both conventional and

TABLE I: GMPP for all PV arrays in all shading conditions

Shadings	SP (W)	TCT (W)	BL (W)	HC (W)	MB (W)	hybrid SP-TCT (W)	hybrid BL-TCT (W)	hybrid HC-TCT (W)
Case-I(a)	2100	2100	2053	2000	2000	2090	2030	2100
Case-I(b)	1900	1900	1900	1900	1900	1900	1900	1900
Case-II(a)	2380	2450	2400	2400	2410	2400	2450	2420
Case-II(b)	1320	1320	1320	1320	1320	1320	1320	1320
Case-III(a)	1350	1800	1800	1520	1520	1500	1800	1530
Case-III(b)	1470	2008	1520	1550	1550	1994	2007	1990

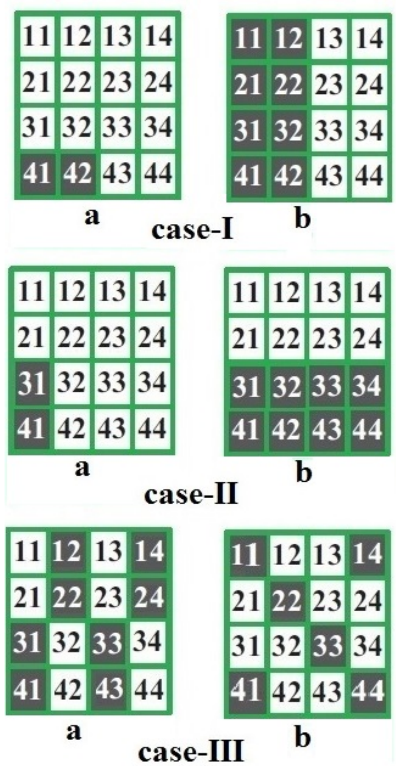

Fig. 4: Different Shading Conditions

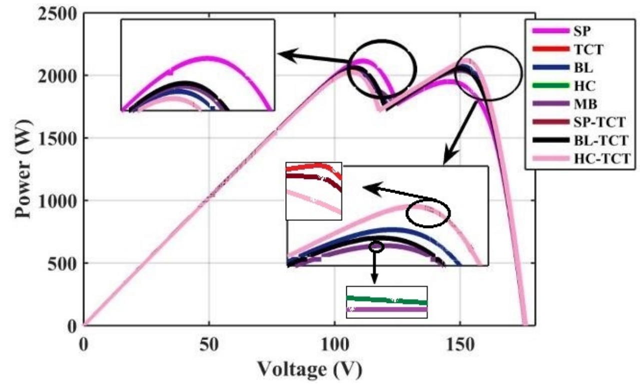

Fig. 5: P-V curve for case-I(a)

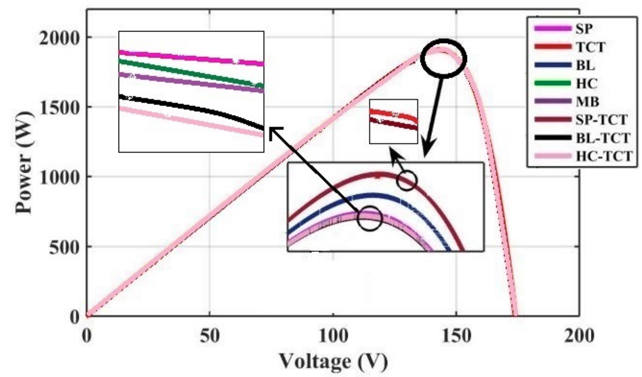

Fig. 6: P-V curve for case-I(b)

hybrid PV arrays. However, the SP, TCT and hybrid HC-TCT PV arrays are producing real GMPP in this shading case-I(a). The obtained GMPP for all PV arrays is given in Table I. The PV characteristics of PV array configurations for shading case-I (b) as shown in Fig.6. From the figure, it is observed that both conventional and hybrid configurations are exhibits one maximum power point (MPP). In this shading, all configurations are producing same GMPP which is given in Table I.

B. Performance of PV arrays configurations under shading case-II

The P-V characteristics of PV array configurations for shading case-II are shown in Figs.7-8. In shading case-II (a), the various multiple peaks are observed on the PV curve as shown in Fig.7. From the figure, it is observed that local peaks are far away from the global peaks for both conventional and hybrid PV arrays. However, the TCT and hybrid BL-TCT PV arrays are producing real GMPP in this shading case-II(a). The obtained global maximum power outputs for all PV arrays is shown in Table I. In shading case-II(b),the various multiple peaks are observed on the PV curve as shown in Fig.8. From the figure, it is observed that all PV array configurations are producing equal GMPP for all PV arrays which is given in Table I.

C. Performance of PV arrays configurations under shading case-III

The P-V characteristics of PV array configurations for shading case-III are shown in Figs.9-10. In shading case-III (a), each PV array configuration are exhibits multiple peaks which is shown in Fig.9. Among all multiple peaks, the TCT, BL and hybrid BL-TCT are producing real GMPP in this shading case-III(a). The obtained GMPP for all PV arrays observed in Table.I. In shading case-III (b), the various multiple peaks are observed on the PV curve as shown in Fig. 10. Among all multiple peaks, the TCT and hybrid BL-TCT are producing real global maximum power in this shading case-III(b). The

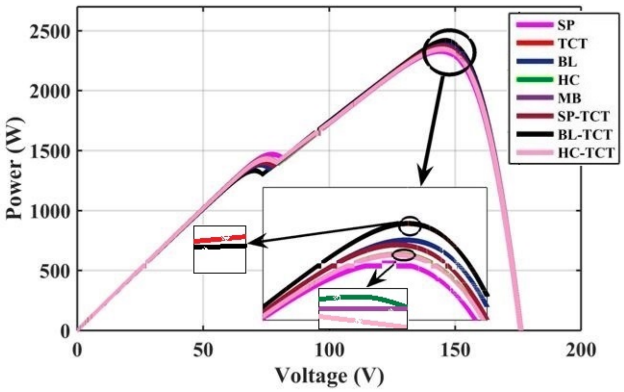

Fig. 7: P-V curve for case-II(a)

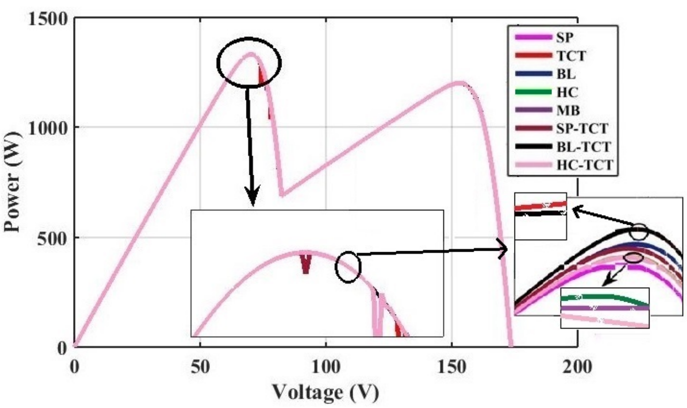

Fig. 8: P-V curve for case-II(b)

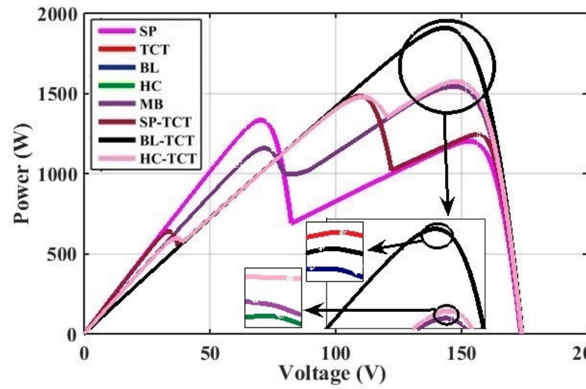

Fig. 9: P-V curve for case-III(a)

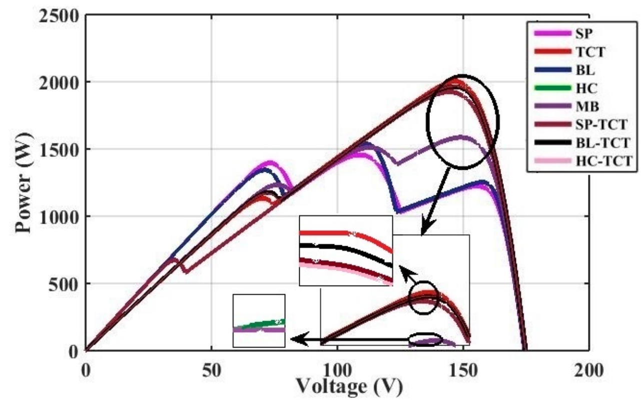

Fig. 10: P-V curve for case-III(b)

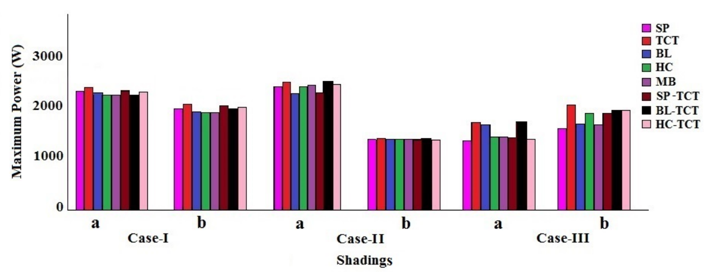

Fig. 11: GMPP in all shading cases

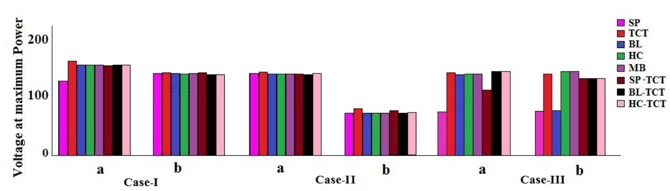

Fig. 12: voltage at GMPP in all shading cases

obtained GMPP outputs for all PV arrays is given in Table I.

For all shading conditions, the obtained parameters such as GMPP, V_{GMPP}, fill factor and possible local peaks for all PV array configurations are also represented graphically in Figs. 11-14.

From aforementioned studies, it can be inferred that under conventional configurations, the TCT PV array is producing highest GMPP than the other configurations under most shading cases. In hybrid configurations, the BL-TCT PV array is showing better performance among all.

V. CONCLUSION

This paper is mainly focusing on the study of partial shading effects on different conventional and hybrid PV array configurations. In this study "SP, TCT, BL, HC, MB, hybrid SP-TCT, hybrid BL-TCT and hybrid HC-TCT" PV array configurations are considered for partial shading analysis. The simulation studies are carried out on 4×4 PV array by using MATLAB-SIMULINK and then comparing various parameters. From the simulation results, it is observed that the TCT PV array configuration is produced highest GMPP and has high fill factor as compared to all other configurations under most shading cases. Also, the generated GMPP of hybrid BL-TCT configuration is equal to the TCT, which is higher than the all other configurations.

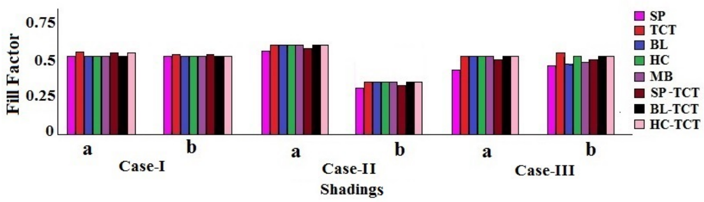

Fig. 13: fill factor in all shading cases

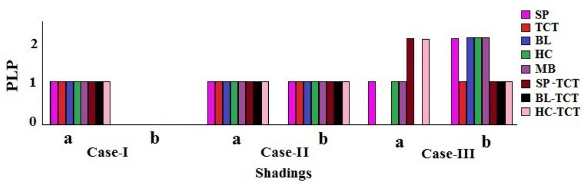

Fig. 14: possible local peaks in all shading cases

References

[1] S. K. Sahoo, "Renewable and sustainable energy reviews solar photovoltaic energy progress in india: A review," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 927–939, 2016.

[2] N. Sahoo, I. Elamvazuthi, N. M. Nor, P. Sebastian, and B. Lim, "Pv panel modelling using simscape," in *Energy, Automation, and Signal (ICEAS), 2011 International Conference on*, pp. 1–4, IEEE, 2011.

[3] H. Tian, F. Mancilla-David, K. Ellis, E. Muljadi, and P. Jenkins, "A cell-to-module-to-array detailed model for photovoltaic panels," *Solar energy*, vol. 86, no. 9, pp. 2695–2706, 2012.

[4] M. S. El-Dein, M. Kazerani, and M. Salama, "An optimal total cross tied interconnection for reducing mismatch losses in photovoltaic arrays," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 99–107, 2013.

[5] 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, 2011.

[6] M. S. El-Dein, M. Kazerani, and M. Salama, "Optimal photovoltaic array reconfiguration to reduce partial shading losses," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 145–153, 2013.

[7] P. S. Rao, G. S. Ilango, and C. Nagamani, "Maximum power from pv arrays using a fixed configuration under different shading conditions," *IEEE journal of Photovoltaics*, vol. 4, no. 2, pp. 679–686, 2014.

[8] O. Bingöl and B. Özkaya, "Analysis and comparison of different pv array configurations under partial shading conditions," *Solar Energy*, vol. 160, pp. 336–343, 2018.

[9] A. S. Yadav, R. K. Pachauri, and Y. K. Chauhan, "Comprehensive investigation of pv arrays with puzzle shade dispersion for improved performance," *Solar Energy*, vol. 129, pp. 256–285, 2016.

[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, 2010.

[11] R. P. Vengatesh and S. E. Rajan, "Analysis of pv module connected in different configurations under uniform and non-uniform solar radiations," *International Journal of Green Energy*, vol. 13, no. 14, pp. 1507–1516, 2016.

[12] R. Ramaprabha and B. Mathur, "A comprehensive review and analysis of solar photovoltaic array configurations under partial shaded conditions," *International Journal of Photoenergy*, vol. 2012, 2012.

[13] R. Ramaprabha, B. Mathur, M. Murthy, and S. Madhumitha, "New configuration of solar photo voltaic array to address partial shaded conditions," pp. 328–333, 2010.

[14] 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, 2008.

[15] M. Hasan and S. Parida, "An overview of solar photovoltaic panel modeling based on analytical and experimental viewpoint," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 75–83, 2016.