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Performance assessment of basic and hybrid photovoltaic array configurations under partially shaded conditions

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Research Article

Performance assessment of basic and hybrid photovoltaic array configurations under partially shaded conditions

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Abstract

Photovoltaic (PV) production systems are facing various issues during the partial shading conditions (PSCs). This can in turn affect the maximum production of power and the proficiency or capability of the system. By reducing the imbalance in power losses during considered partial shading conditions, the primary centre of attention of this research work is to model and replicate various PV array configurations as a way to extricate the maximum power production, and to analyze the output characteristics and to examine and compare the competence efficiency of PV array configurations under the same. In this work performance of basic PV, array configurations are compared with the performance of hybrid configurations. The maximum power generated, fill factors, shading losses, relative losses and performance ratios of different PV configurations are analyzed in this work.

Keywords: Photovoltaic systems, partial shading, maximum power, power conversion, shading losses

Introduction

The growing human population highly enhances the world's demand for energy. This ever-increasing demand is mainly satisfied by the blind use of fossil fuels, though these non-renewable sources of energy are under rapid devastation day-by-day, causing substantial environmental destruction [1]. It can be well stated that the energy accessibility in developing countries like India is very much closely interlinked with the socio-economic development process happening in the country [2]. One way to abolish all the specific issues of energy access would be by embracing solar energy. Because solar power is readily accessible and free to harness, the acceptability and the use of solar or photovoltaic energy has become rampant and universal [3]. Solar power is attaining its due prominence because of the sudden fall-off in the cost of PV cells, along with the extensive and essential technological advancements in the field of power electronics [4]. One of the main problems in the reduction of power output from the SPV array is partial shading. The leading causes of partial shading include the canopy of various big trees, shadows of nearby huge buildings or chimneys nearby, dust, dirt, and so on [5].

The shading upon the panels shields the total absorption of sunlight, minimizing the energy received by the cells. The resultant hike in the heat up and the formation of hotspots in the PV modules, destruct the entire system [6]. Fixing the bypass diodes in each cell would be a preferable solution for partial shading, but it will not be much feasible when it comes to the case of capital investment needed [7]. In the standard uniform solar insolation condition, only one maximum power point (MPP) would exist. But in the case of partial shading, the SPV systems with bypass diodes would generate multiple MPP's, in the individual power curve of the SPV system, among which the only one will be treated as a global maximum power point (GMPP), and the rest are treated as local maximum power points (LMPPs). However, the usual methods of tracking MPP are not effective enough to do the same with GMPP [8].

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Much extensive research is carried out regarding this and theses methods are distinct in their tracking speed, expense, use of the number of sensors, and so on for tracking GMPP [9]. The rearranging of the modules would compensate for the losses related to the shading effect. The prominent interconnection methods highlighted in the literature are SP, TCT, BL configurations and hybrid combinations of basic configurations are also possible [10].

SP configuration is less complicated as the modules are connected in series and later connected in parallel by reducing the time required for installation of the entire SPV system. But, the impact of partial shading is highly visible in this type of configuration. The additional interconnections in the TCT configurations help in minimizing the probability of unnecessary switching of bypass diodes during partial shading conditions [11]. A relative analysis or scrutiny was prepared on the competence of various PV array topologies like SP, BL, and TCT in many different irradiance conditions. The simulation models were carried out by making use of Matlab software and competence was assessed by connecting and disconnecting bypass diodes, and the study detected that the TCT configuration overpowers the SP and BL configurations within the PSCs examined [12].

The SP, TCT, and BL tie-in plans for shifting shade on the 4×4 PV array was replicated and examined, to come up with the conclusion that attaining extra power can be done by selecting the right tie-in plan according to the changing patterns of shading. In a study, the power production losses, fill factor (FF), etc. was prepared for SP, TCT, and BL PV array configurations. It was pointed out that among all the configurations the TCT configuration has a better competent result [13, 14].

By taking inspiration from the above literature, a comparison of available basic configurations and hybrid configurations is performed for various partial shading patterns in a 4×4 PV array. The performance of basic configurations like SP, BL, HC, TCT and hybrid configurations like SP-TCT, BL-TCT, and BL-HC are compared in this work.

PV modelling

Varied designs are advanced by the researchers to conduct the study on the competence efficiency of the PV arrays within the non-static atmospheric conditions and during the situations of partial shadowing [15]. The most frequently sketched out models are that of the single diode and two diodes [16]. The implementation of PV cells with a single diode is used here. An analogous PV cell circuit includes a current source parallel to the photodiode, a shunt resistance, and series resistance. This circuit is depicted in Fig 1(A)

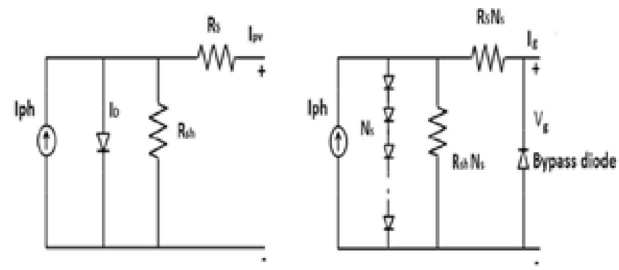


Fig 1A: Equivalent circuit of the solar cell; 1B: Equivalent circuit of PV panel with bypass diode

Table 1: PV module parameters for Matlab modelling and validation at STC (1000 W/m2 and 25°C)

Parameters of PV module	Designed PV module for validation
Maximum power (P_{mpp})	20.07 W
Maximum voltage corresponding to maximum power (V_{mpp})	17.49 V
Maximum current corresponding to maximum power (I_{mpp})	1.13 A
Open circuit voltage (V_{oc})	20.68 V
Short circuit current (I_{sc})	1.23 A

The different features of commercially available PV panel AS2012 ANDSLITE at STC are used for the implementation and validation of the PV module in MATLAB/Simulink and are given in Table 1. I-V characteristics and P-V characteristics of modelled PV modules at various solar insolation levels and a temperature of 25°C are shown in Figs 2 and 3.

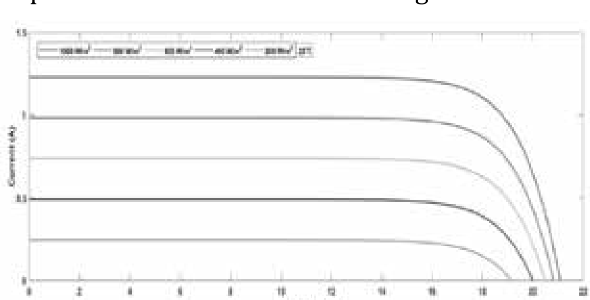


Fig 2: I-V characteristics of PV panel at the different insolation level and temperature of 25°C

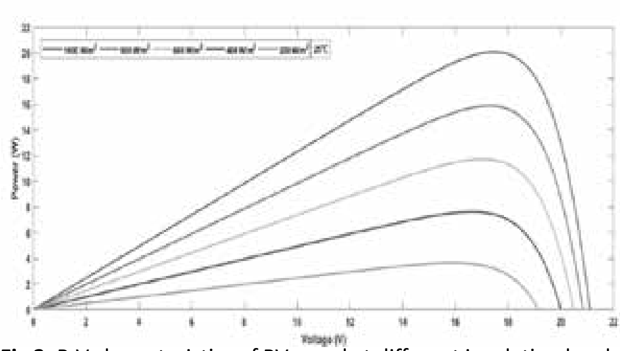


Fig 3: P-V characteristics of PV panel at different insolation levels and temperature of 25°C

Effects of partial shading

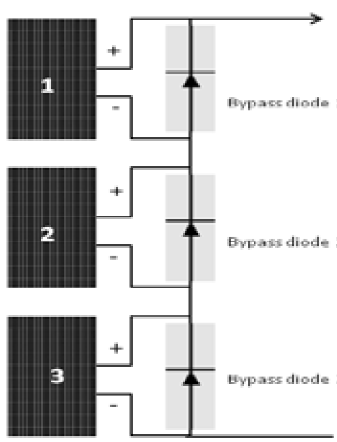


Fig 4: Schematic diagram of three panels linked in series with three bypass diodes.

The designed PV model is meant for replicating and validating the various situations of partial shading. Within the case of unwavering insolation and a constant temperature, every panel would be exhibiting a constant and a stable electrical trait, and only a single MPP would be entertained by the whole PV configuration. Whereas during the partial shading, rather than behaving like a power generating source, the whole panel will work as a load. It results in the formation of hotspots within the shadowed panels. The usage of such panels for a prolonged period would result in the permanent destruction of the panels. To prevent this damage, bypass diodes are affixed to its parallel in opposite directions. Therefore, when constant solar radiation is received by the panels, these diodes will work in a reverse-biased state, and during the condition of partial shading, the diode works in a forward-biased state, promoting the flow of current through the diodes.

A combination of three PV panels connected in series is designed here, as shown in Fig 4, and it is used to analyze the effects of progressive type partial shading in the PV panels in this pattern. Four cases are considered here in case 1, all the three panels are under uniform insolation level and get maximum power of 60.25 W. In case 2, the third panel is shaded and gets insolation of 500 W/m2 and the other two panels are not shaded, making the maximum power gets reduced to 39.25 W. In case 3, the second and third panels are shaded and receive insolation of 500 W/m2, and panel one is left unshaded. The power obtained here is only 31.03 W. In the last case, all the panels are shaded and the power output is reduced to 28.97 W. The corresponding electrical characteristics of three panels connected in series are shown in Figs 5(A) and 5(B).

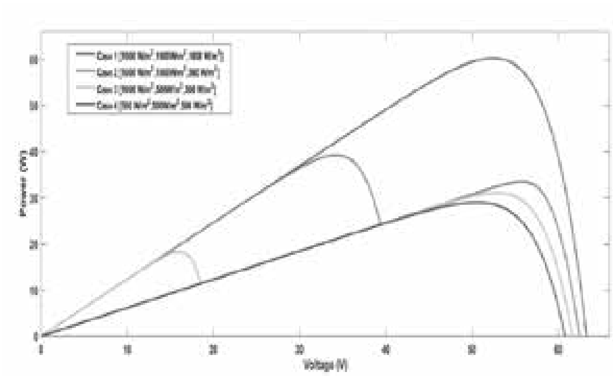


Fig 5 (A): P-V characteristics under shading effects on three PV panels connected in series.

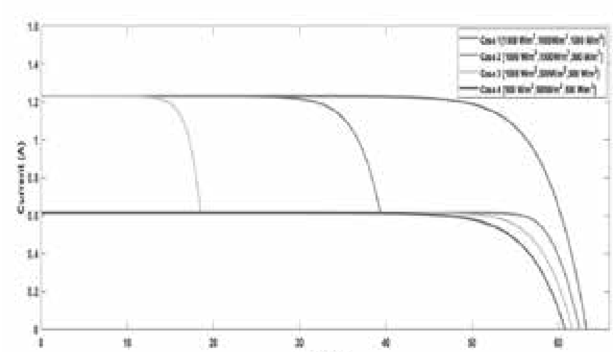


Fig 5 (B): I-V characteristics under progressive shading of three PV panels connected in series.

Various PV array configurations

The basic connections such as series parallel (SP), bridged link (BL), honey comb (HC), total cross-tied (TCT); and the combinations of these basic configurations such as series parallel-total cross-tied (SP-TCT), bridged link–total cross-tied (BL-TCT), bridged link-honeycomb (BL-HC) are studied in this paper. All connections are considered for a 4×4 PV array. In this research, the PV array is composed of 16 PV modules. Each module is numbered in ascending order from top to bottom and from the left to the right direction, with the first and second numerals representing the row and column of the arranged pattern. The schematic diagrams of different conventional PV array configurations like SP, BL, HC, TCT; hybrid configurations like SP-TCT, BL-TCT and BL-HC with the number of interconnections are shown in Fig 6.

The SP connection is a combination of simple series and simple parallel configurations. For attaining the desired output voltage level, all panels are first linked in a series pattern and then these are again linked in parallel. The BL connection is the combination of modules in a bridge rectifier manner. There are five interconnections in BL configuration for a 4×4 PV array. The voltages and currents are acquired by suitably summing voltages in series and currents in parallel. The HC connection is the modification of the BL connection. There are five interconnections in HC configuration for a 4×4 PV array. The TCT configuration is the modification of SP configuration; obtained by connecting cross ties between each row of modules. In the TCT method, the total sum of current across each column is equal and the voltage across each row is equal too. There are nine interconnections in TCT configuration for a 4×4 PV array. The SP-TCT configuration is a combination of SP and TCT configuration. There are three interconnections in the SP-TCT configuration for a 4×4 PV array. The BL-TCT connection is a mix of BL and TCT methods. There are seven interconnections in BL-TCT configuration for a 4×4 PV array. The BL-HC interconnection is a combination of BL and HC connections. There are eight interconnections in BL-HC configuration for a 4×4 PV array.

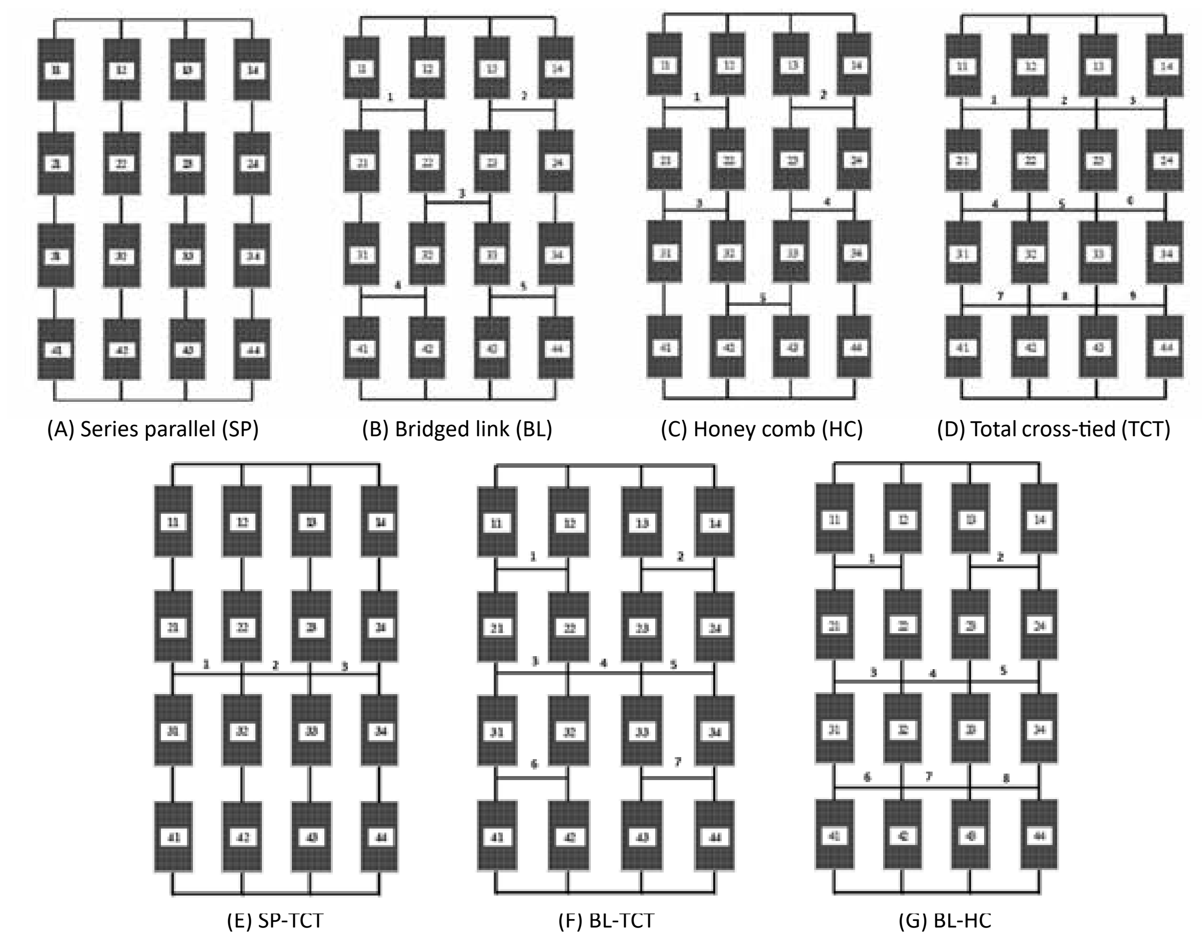


Fig 6: (A) SP configuration; (B) BL configuration; (C) HC configuration; (D) TCT configuration; (E) SP-TCT configuration; (F) BL-TCT configuration; (G) BL-HC configuration

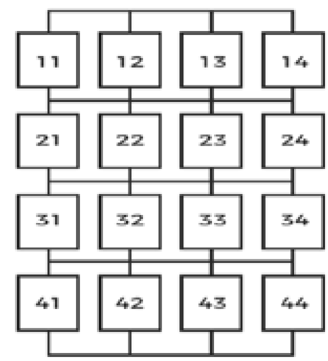
Shading effects on PV panels

The shading effect upon the panels reduces the power production from it. Though various configuration patterns become helpful in reducing the lack of production from these affected panels, it cannot fully resolve the issue. The case study that has been chosen here is a special way of shading and this particular pattern of shading builds a huge loss in power production from the implanted panels.

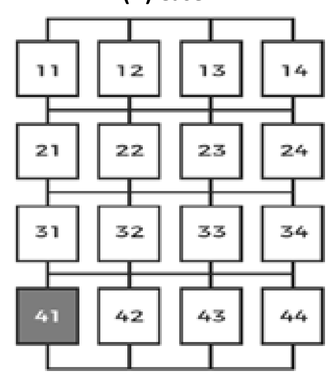
It is found that with the change in the location of the sun, the shifting and enhancing of the shadow of a particular hindrance nearby the panels, gradually and rapidly reduces the efficient power production from these panels. It is very adamantly found that in most of the cases, the shadowing first affects a single panel in a row, and with a change in the position of the sun, the shadowing effects the other panels nearby - one by one; and thus, affecting the entire panels rapidly within a very short countable period.

Considering the theoretical and practical points of view, the following cases of shading patterns as shown in Fig 7, are chosen for the study and comparison. The case 1 is the normal uniform shading condition, wherein no panel will be shaded and thus there would be only a single maximum peak point. Thus, this particular case is used for the comparison of performance results in the chosen shading cases for the study. Cases 2-5 depicts the row-wise progressive shading pattern, where the shade progressively enhances throughout the entire panels in a row. Case 6 describes the corner type-shading pattern, wherein the corner panels get completely shaded and this could be taken as one of the most practically probable shading cases. Cases 7 and 8 indicate the L shape-shading pattern, which occurs due to the shading of obstacles from either two sides. Case 9 stipulate enhancing corner-grid pattern of shading, the kind of shading practically caused by huge constructions like multi-complex buildings nearby.

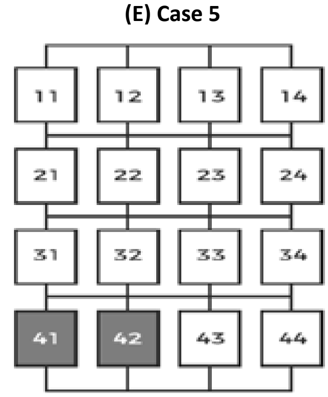
The hypothesis of Matlab simulation includes the development of a PV module using the specifications of Andslite 20 W panel. During the modelling of PV module using a single diode model, the only series resistance is considered and shunt resistance is neglected. The modelled PV module is used to create the basic configurations and hybrid configurations for a 4×4 PV array. The various shading patterns are studied on these configurations. The unshaded panels receive insolation of 1000 W/m2 and shaded panels receive insolation of 500 W/m2 at a temperature of 25°C. During partially shaded conditions, the effects of series resistance, shunt resistance, and bypass diode voltage drops are neglected. Neglecting the fringing effect, only the desired module will receive the partial irradiance during the different patterns of shading. To study the performance of the configurations, the maximum power points, fill factor, partial shading losses, relative losses, and performance ratios are analyzed.

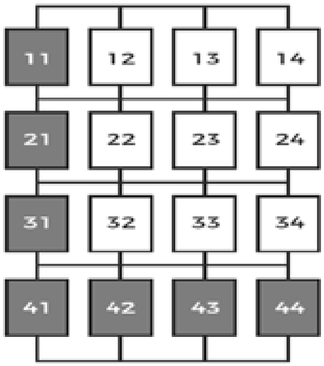


(A) Case 1
(D) Case 4

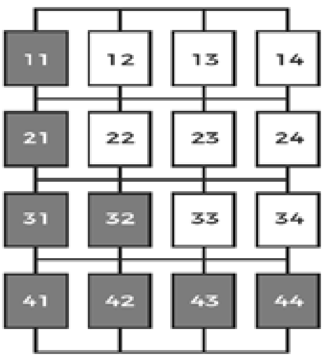


(B) Case 2
(E) Case 5

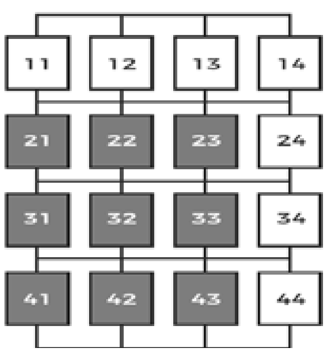




Case 7



(H) Case 8



(I) Case 9

Fig 7: Shading cases (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

Results and discussion

Performance analysis parameters

Fill factor

The power losses in PSCs highly concern the value of fill factor (FF) of a PV array [17]. The parameter FF directly leans over the open-circuit voltage and short circuit current of the PV array, examined at the P-V and I-V characteristics. The FF can be approximated as,

$$Fill\ Factor = FF = \frac{V_{mpp} I_{mpp}}{V_{oc} I_{sc}}$$

Estimation of fill factor for case 1 is illustrated in Fig 8.

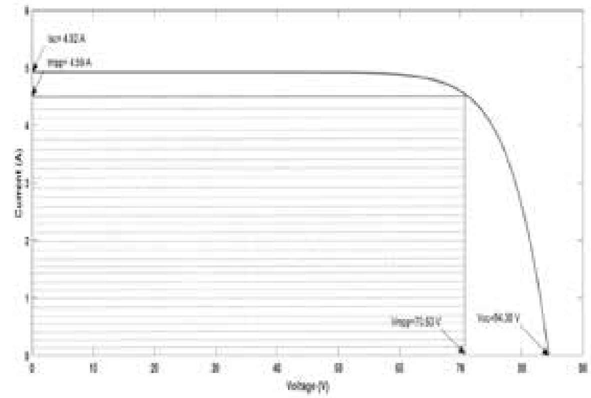


Fig 8: Estimation of fill factor of designed 4×4 PV array using IV characteristics under STC.

Pshading losses

The main losses of PV arrays during partial shading are mismatch power losses, expressed as the difference between the under the uniform condition at STC and Pmpp under partial shading conditions [18].

Partial shading losses

= Pmpp under uniform condition at STC - Pmpp under partial shaded condition

Estimation of partial shading losses is illustrated in Fig 9.

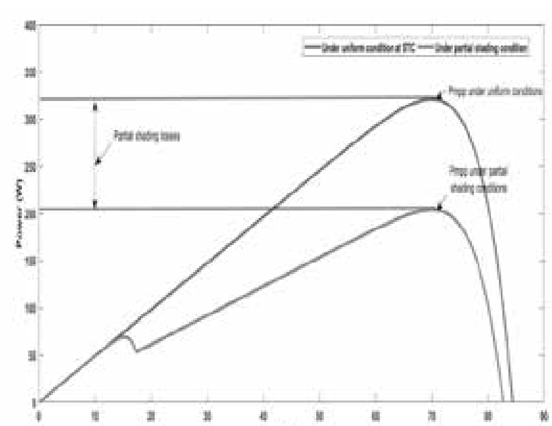


Fig 9: Estimation of partial shading losses

Relative losses

Relative power losses are given by;

Relative power losses are given by;

$$Relative\ Power\ losses = \frac{(P_{mpp}\ \text{under uniform condition at STC} - P_{mpp}\ \text{under partial shaded condition})}{P_{mpp}\ \text{under uniform condition at STC}} \times 100$$

Performance ratio

The performance ratio is obtained by;

$$Performance\ ratio = \frac{P_{mpp}\ \text{under partial shaded conditions}}{P_{mpp}\ \text{under uniform condition at STC}} \times 100$$

Table 2: Consolidated parameters of partial shading effects in basic configurations

	Type	Pmpp (W)	FF (%)	Partial shading losses (W)	Relative loss (%)	PR (%)
Case 1	SP	321.40	77.91	0.00	0.00	100.00
	BL	321.40	77.91	0.00	0.00	100.00
	HC	321.40	77.91	0.00	0.00	100.00
	TCT	321.40	77.91	0.00	0.00	100.00
Case 2	SP	284.20	69.13	37.20	11.57	88.43
	BL	295.40	71.86	26.00	8.09	91.91
	HC	289.10	70.33	32.30	10.05	89.95
	TCT	300.60	73.11	20.80	6.47	93.53
Case 3	SP	248.90	60.52	72.50	22.56	77.44
	BL	255.90	62.25	65.50	20.38	79.62
	HC	260.90	63.46	60.50	18.82	81.18
	TCT	265.60	64.62	55.80	17.36	82.64
Case 4	SP	242.10	58.90	79.30	24.67	75.33
	BL	237.30	57.74	84.10	26.17	73.83
	HC	239.10	58.18	82.30	25.61	74.39
	TCT	237.30	57.74	84.10	26.17	73.83
Case 5	SP	237.50	58.30	83.90	26.10	73.90
	BL	237.50	58.30	83.90	26.10	73.90
	HC	237.50	58.30	83.90	26.10	73.90
	TCT	237.50	58.30	83.90	26.10	73.90
Case 6	SP	245.90	59.83	75.50	23.49	76.51
	BL	251.50	61.23	69.90	21.75	78.25
	HC	245.40	59.72	76.00	23.65	76.35
	TCT	254.50	61.96	66.90	20.82	79.18
Case 7	SP	209.80	58.91	111.60	34.72	65.28
	BL	206.10	57.86	115.30	35.87	64.13
	HC	207.60	58.29	113.80	35.41	64.59
	TCT	206.10	57.86	115.30	35.87	64.13
Case 8	SP	189.00	51.40	132.40	41.19	58.81
	BL	189.70	53.28	131.70	40.98	59.02
	HC	182.60	51.29	138.80	43.19	56.81
	TCT	187.90	52.81	133.50	41.54	58.46
Case 9	SP	207.10	50.91	114.30	35.56	64.44
	BL	170.30	42.40	151.10	47.01	52.99
	HC	203.90	50.76	117.50	36.56	63.44
	TCT	204.20	50.83	117.20	36.47	63.53

Performance assessment of basic PV array configurations is included in Table 2. It is clear from the table that the performance of TCT configuration is better than SP, HC, and BL basic configuration in almost all cases under study. In Table 3, the consolidated analysis of parameters of hybrid configurations under different shading conditions is given. Here, in three cases, SP-TCT, BL-TCT and BL-HC configurations have equal performance. In few cases taken for study, BL-HC performs well compared to others and in some other cases, SP-TCT configurations work in a better manner. However, the performance of TCT is either higher than or equal to that of those hybrid configurations considered here for the study.

Table 3: Consolidated parameters of partial shading effects in hybrid configurations

	Type	Pmpp	FF	Partial shading losses	Relative loss	PR
		W	(%)	W	(%)	(%)
Case 1	SP-TCT	321.40	77.91	0.00	0.00	100.00
	BL-TCT	321.40	77.91	0.00	0.00	100.00
	BL-HC	321.40	77.91	0.00	0.00	100.00
Case 2	SP-TCT	294.30	72.28	27.10	8.43	91.57
	BL-TCT	296.90	72.23	24.50	7.62	92.38
	BL-HC	300.60	72.24	20.80	6.47	93.53
Case 3	SP-TCT	259.20	62.51	62.20	19.35	80.65
	BL-TCT	259.20	63.04	62.20	19.35	80.65
	BL-HC	265.60	64.62	55.80	17.36	82.64
Case 4	SP-TCT	238.90	58.13	82.50	25.67	74.33
	BL-TCT	237.30	57.74	84.10	26.17	73.83
	BL-HC	237.30	57.74	84.10	26.17	73.83
Case 5	SP-TCT	237.50	58.30	83.90	26.10	73.90
	BL-TCT	237.50	58.30	83.90	26.10	73.90
	BL-HC	237.50	58.30	83.90	26.10	73.90
Case 6	SP-TCT	254.50	61.96	66.90	20.82	79.18
	BL-TCT	254.50	61.96	66.90	20.82	79.18
	BL-HC	254.50	61.96	66.90	20.82	79.18
Case 7	SP-TCT	207.50	58.25	113.90	35.44	64.56
	BL-TCT	206.10	57.63	115.30	35.87	64.13
	BL-HC	206.10	57.63	115.30	35.87	64.13
Case 8	SP-TCT	190.60	53.56	130.80	40.70	59.30
	BL-TCT	190.60	53.56	130.80	40.70	59.30
	BL-HC	187.90	52.81	133.50	41.54	58.46
Case 9	SP-TCT	202.10	50.26	119.30	37.12	62.88
	BL-TCT	174.70	43.48	146.70	45.64	54.36
	BL-HC	203.80	50.73	117.60	36.59	63.41

Conclusion

This paper determines the competence efficiency of basic conventional PV array configurations, and hybrid PV array configurations during partial shading. Simulations of these configurations are implemented for 4×4 PV array under progressive shading, corner shading, L shaped shading and corner grid shading. Nine different cases of shading are analyzed for seven different PV array configurations. The assessment of various PV array configurations in the study proved that TCT and BL-HC arrangement gives a comparatively better performance within the cases of considered shading. Maximum power, fill factor, relative power losses and shading losses are studied for the assessment of the performance of PV array configurations.

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