

Received November 14, 2020, accepted November 25, 2020, date of publication December 1, 2020, date of current version December 14, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3041715

Investigation of Different BPD Placement Topologies for Shaded Modules in a Series-Parallel Configured PV Array

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ABSTRACT This article investigates the performance of serial-parallel (SP) configuration of photovoltaic (PV) array under artificial arrangement for partial shading conditions (PSCs). The concept of bypass diode (BPD) is a very attractive solution to reduce the shading effect on the PV module and therefore gives better performance in such shading environment types. Various bypass diode integration (BPD) placement topologies with the solar photovoltaic (PV) modules are being investigated to demonstrate the improved performance under PSCs in the current work. The sixteen PV modules arranged in SP configuration are associated with the BPD Topologies such as (a) Without bypass diode (W-BPD) (b), Single string- single bypass diode (SS-SBPD) (c) Single string- double bypass diode (SS-DBPD) (d) Series group- bypass diode (G-BPD) (e) Staggered group- bypass diode (SG-BPD) (f) Multi level-octal bypass diode (ML-OBPD) for performance investigation. The performance assessment for all PV array supported by BPD topologies has been investigated using current –voltage (I –V) and power –voltage (P –V) characteristics and comparing to show better power and voltage results at global maximum power point (GMPP), improved fill factor and minimized power losses etc. The results presented may be recommended for the appropriate PV array configuration interconnection of BPD. Overall, this article reports that the ML-OBPD based SP configured PV array is superior among the BPD topologies under the considered PSTCs.


INDEX TERMS Bypass diode, shading effect, fill factor, global maximum power point, power loss.

NOMENCLATURE

W-BPD	Without bypass diode
SS-SBPD	Single string-single bypass diode
SS-DBPD	Single string-double bypass diode
Series G-BPD	Series group-bypass diode
SG-BPD	Staggered group-bypass diode
ML-OBPD	Multi level-octal bypass diode

I. INTRODUCTION

The BPDs have the capacity to reduce the hot spot problem that may damage PV cells and even cause fire if the illumination of the PV cell's surface in a PV module is not consistent. The BPDs are usually placed on the sub - strings of the PV module, one diode per up to 20 PV cells. This BPDs arrangement eliminates the creation of hot spots and allows the PV modules throughout their lifetime to operate

The associate editor coordinating the review of this manuscript and approving it for publication was Tariq Masood .

with high reliability. In addition to effectively performing this function, many people believe that BPDs are also effective in reducing in power loss due to shading in PV installations. The reduction of output power in solar photovoltaic systems is observed due to many factors such as technical and environmental aspects. The mismatch power losses introduced and considered major causes of power reduction in today's research era due to the shading effect on PV system performance.

In this direction, the authors of [1] noted that shaded PV module/cells function as a load rather than as power generators under PSCs. Similarly, the shaded PV modules/ cells damaged due to a hot spot phenomenon when the reverse bias breakdown voltage exceeds [2]. Specifically, when hotspot is on a small section of PV modules, it covers the causes of reducing the output power of high-power degeneration PV systems. After some time, it can damage the PV module as explained in [3]. In [4], the authors have investigated that the output power of PV arrays can be improved if BPDs are

connected with the PV modules in an antiparallel manner. The performance of the PV array also depends on the type of BPD connection topologies [5]. Two different topologies of the BPD connection have been reported and extensive performance analysis has been reported in [6]. Topologies of overlapping and non-overlapping BPD (OBPD, N-OBPD). PV modules such as series (S), parallel (P), series-parallel (SP), bridge connection (BL), total-cross-tied (TCT) and honeycomb (HC) under PSCs are arranged. The authors studied and compared topologies in PV strings with OBPD and N-OBPD [7]. As shown in [8], the normalized power of parallel connected PV modules is higher than the series type of PV arrays in a shading spot such as the translucent and opaque type. In [9], the authors focused on reducing the output power of PV arrays under PSCs by 31% and generating only global maximum power points (GMPPs) when no BPD is connected in PV arrays. It is shown in [10] that BPD increases output power and current flowing through the PV modules but also generates multiple GMPPs at the same time. In [11], the authors found that the value of short circuit current (I_{SC}) in N-OBPD-based PV systems is higher than those based on W-BPD. In this regard, the TCT PV array type N-OBPD generates multiple numbers of local MPPs, making it difficult to track GMPPs. In addition, the efficiency of the N-OBPD-based TCT array is 10% higher than the N-OBPD based SP array [12]. According to [13], the TCT configuration is more capable of reducing mismatch losses than other conventional configurations. The N-OBPD type TCT array MPPs may also vary due to varying environmental conditions, but the fact remains that their performance is higher than other configurations as reported in [14]. In addition, the N-based TCT configuration OBPD enhances power generation by 5.8% compared to the W-BPD configuration type of TCT [15]. The authors of [16] studied and developed the PV arrays based on the switching circuit and observed that the number of MPPs based on the switching circuit on PV arrays is lower than in the case of PV array type N-OBPD. Recently, Rani *et al.* [17] introduced the PV array configuration which is based on Su-Do-Ku (SDK) puzzle and compared the performance between SDK and TCT configurations. It is found that the SDK configuration reduces the predominant shading effects and also improves the generated PV power. The standard GA based PV array configuration is reported in [18] to produce 294W more power than conventional SDK configuration with the N-OBPDs conditions. In [19], a puzzled based PV array configuration with OBPDs topology generates 28.59 % more power than a TCT based configuration. Another approach presented in [20], showed that the adaptive PV array structure based on N-OBPD reduces two MPPs to a single MPP and generates 12% higher output power. The authors of [21] developed a W-BPD Magic -Square (MS) PV Array configuration that provides 44% more output power than traditional TCT based PV configuration. It was pointed out in similar research work in [22] that, under defective conditions, the GMPPs of the reconfigured PV array connection is 4% to 5% higher than

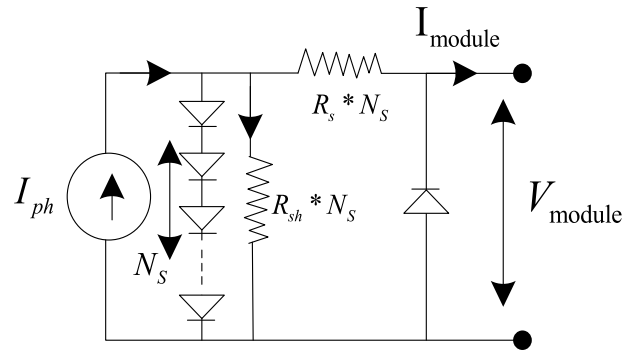


FIGURE 1. Equivalent circuit of a PV cell with BPD [32].

conventional configurations. In [23], the authors have argued that PV array configurations based on the number of methods placed generate 6.2% higher power than TCT configurations dependent on N-OBPDs topology. As indicated in [24], the GMPPs of Futoshiki puzzle based PV array configuration has superior results to the TCT configuration which has N-OBPD topology. Similar to other researchers. In [25], the authors have also designed new PV array connections and have noted that the output power improvement as 8.1%. The authors of [26] designed the novel PV array configurations with N-OBPD topologies, called as new schemes-1&2 (NS-1, & NS-2). NS-1 showed a better performance than the NS-2 and TCT configurations as well as conventional ones.

In [27], [28], large scale PV array sizes as 9×9 , 6×20 , 16×16 and 25×25 are considered for performance investigation under shading scenarios. Metaheuristic-based shade dispersion methods (multi-objective Grey Wolf Optimization, Harris Hawks Optimizer, Artificial Ecosystem Optimization, Particle swarm optimization) are used to reconfigure the TCT connections. In [29], [30], Latest optimization technique such as Flow Regime Algorithm (FRA), Social Mimic Optimization Algorithm (SMOA), Marine Predators Algorithm (MPA) and Rao Optimization Algorithm (ROA) are used to reconfigure TCT and competence square PV array configurations (9×9) to investigate under PSCs. The authors of [31] have investigated conventional PV array configurations such as SP, BL, HC and TCT are compared with three design methods of Su-Do-Ku game puzzle based configurations (Su-Do-Ku, Optimal Su-Do-Ku and Improved Su-Do-Ku) under PSCs. The performance of improved Su-Do-Ku is found best as compare to others.

A. NOVELTY OF WORK

The work reported in this article is based on BPD integration methods to improve the performance of the PV system under PSCs. The electrical connections of PV modules are arranged SP based to design 4×4 PV array configuration. Several characteristics of the present prospect can be described as follows,

- A comprehensive performance investigation of SP connection of PV modules with BPD connections is reported.

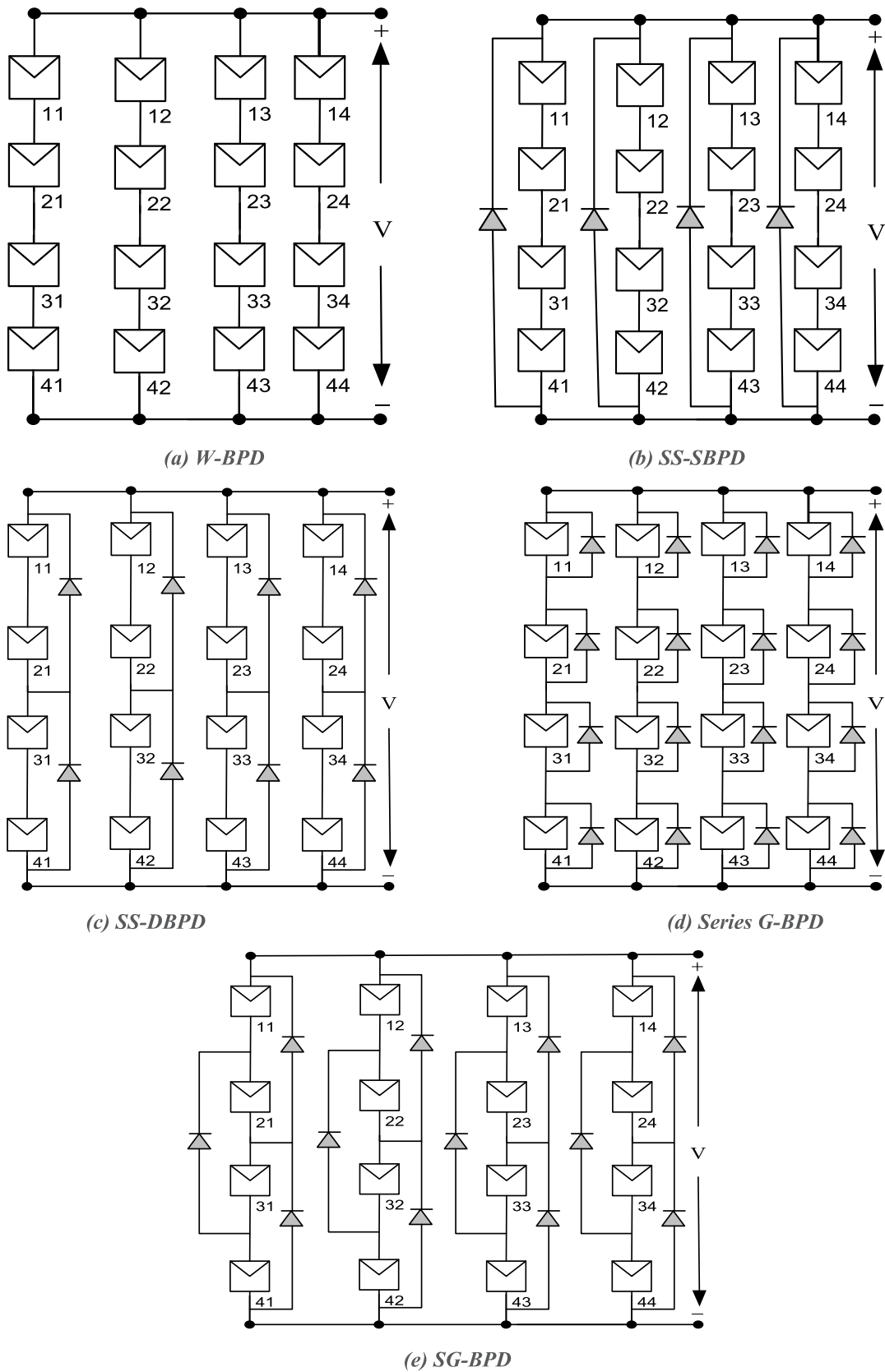


FIGURE 2. (a)-(f). Different topologies of BPDs associated with solar PV module SP- PV array configuration.

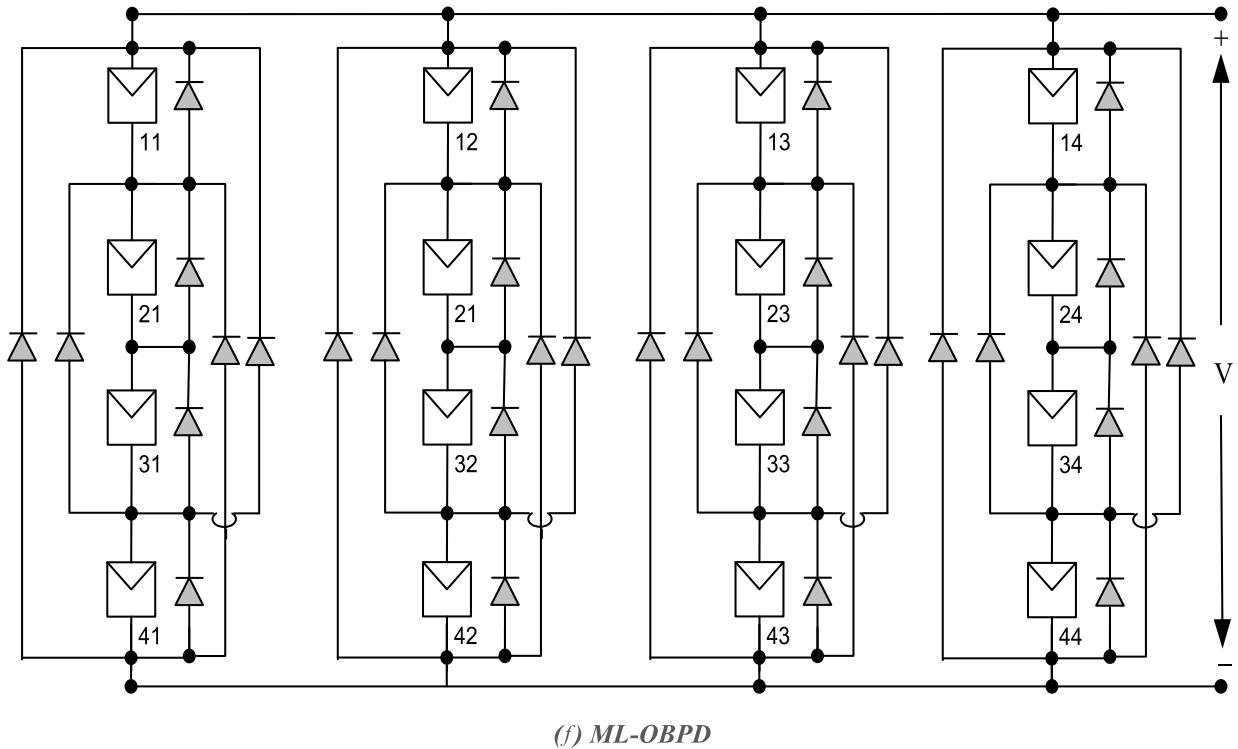


FIGURE 2. (Continued.) (a)-(f). Different topologies of BPDs associated with solar PV module SP- PV array configuration.

- Prospecting performance values for different BPD topologies are analyzed.
- The performance of various BPD topologies integrated with the SP configured PV array is reported in terms of electrical behavior such as P -V and I -V curves.
- ML-OBPD based topology has better performance under four distinguish PSCs and compared to other important BPD topologies.

This article has six sections. Section I presents brief introduction and literature review. The next Section II presents solar PV modelling. Section III describes the topologies of the BPD. Section IV also follows the Analysis of power losses and partial shading test cases. The results and discussion is reported in Section IV. Finally, Section VI presents the conclusion of this work.

II. MODELLING OF PV SYSTEM

The PV module has cascaded similar solar cells, and BPDs are connected in anti-PV mode parallel to PV cells to prevent damage to PV cells by hot spots under PSCs. An equivalent circuit of the BPD integrated PV module is shown in Fig. 1 [32].

Here the equivalent PV circuit is based on Villalva et al. (2009) single diode model [32]. PV cell is considered to be a source of variable current, photo - current (I_{ph}) parallel to the photo diode and can be expressed as,

$$I_{ph} = (I_{SC} + K_i \Delta T) \left(\frac{S}{S_{STC}} \right) \frac{(R_{sh} + R_{se})}{R_{sh}} \quad (1)$$

where, R_{se} and R_{sh} are respectively PV cell shunt and series resistance, I_{SC} – cell s. c. current, S – panel surface insolation, K_i – S. C. current temperature coefficient. Under Standard test conditions (STC): 1000 W/m² insolation and 25°C cell surface temperature [32].

PV panel surface temperature is expressed as,

$$\Delta T = (T - T_{ST}) \quad (2)$$

The module current expression with BPD is shown in Eq. (3) [32] as,

$$I_{mod} = \left\{ I_{ph} - I_0 \left(e^{\frac{q(V_{mod} + R_s I_{pv})}{AKT N_s}} - 1 \right) - \frac{V_{mod} + R_s I_{pv}}{R_{sh} N_s} \right\} + \left\{ I_{obypass} \left(e^{\frac{-q(V_{mod})}{A_{bypass}}} - 1 \right) \right\} \quad (3)$$

where, A – dimensionless material, I_0 – reverse saturation current, K – Boltzmann constant (1.38×10^{-23} J/K), T – Kelvin temperature, and q – electron charge (1.6×10^{-19} C), V_{module} – modular output voltage, N_s – solar cells that in cascade are connected to form a PV panel, R_{s-mod} – series module resistance and R_{sh-mod} – shunt resistance, respectively.

III. BYPASS DIODE TOPOLOGIES FOR SERIES-PARALLEL CONFIGURATION

In SP configuration, total sixteen PV module numbers are arranged to design the PV array. Distinguishing BPD topologies are adopted to show the effect of four types of PSTCs on the PV array. There is no BPD connected to the PV module

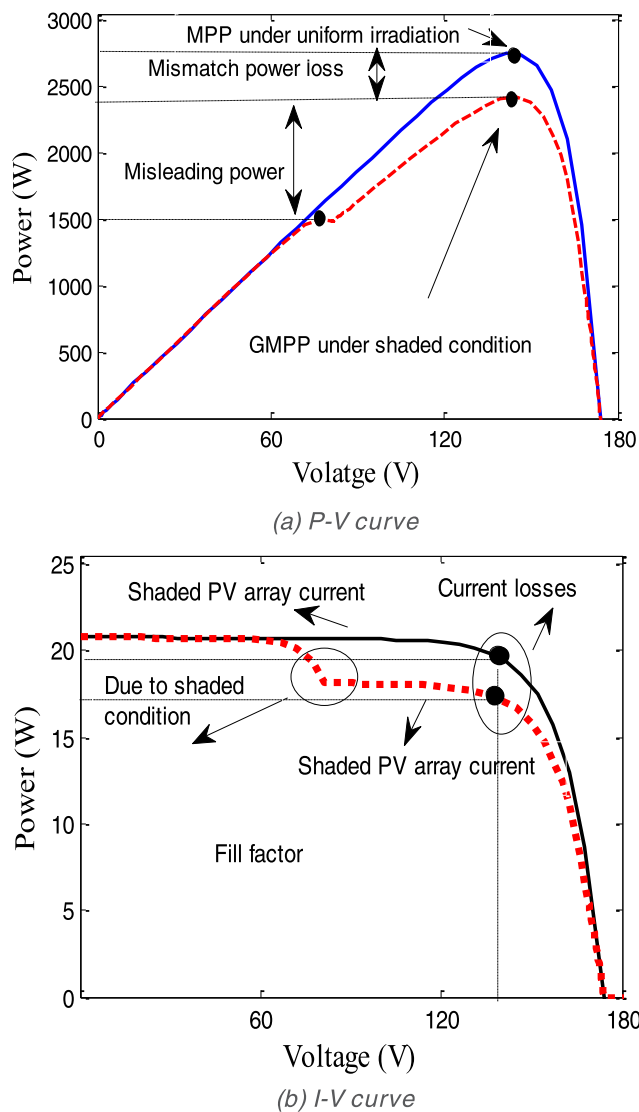


FIGURE 3. P-V and I-V characteristics.

in array in W - BPD - based SP configuration. In the second SS - BPD topology, a single BPD is connected for each string consisting of four PV modules. In SS - DBPD's third topology, two BPDs are connected as overlapping conditions to the two consequence PV modules. In BPD's fourth topology as a Series Group - BPD, all PV modules have a single BPD separately. BPD's staggered group topology also has been added one more BPD in the topology of SS - DBPD. A total of eight numbers of BPDs are connected in the last ML- OBPD topology, which is a mixed version of all the topologies discussed. In a single string of PV modules, a total of eight BPD numbers are used in a 4 × 4 size PV array. All topologies of the BPD are shown in Fig. 2(a)-(f) as,

IV. ANALYSIS OF POWER LOSSES AND PSCS

With the PSCs, the maximum power point (MPP) of the PV array does not match the MPP of each PV module, so that a loss of power through different mechanisms is found. When using the bypass diode, the power generated by partially

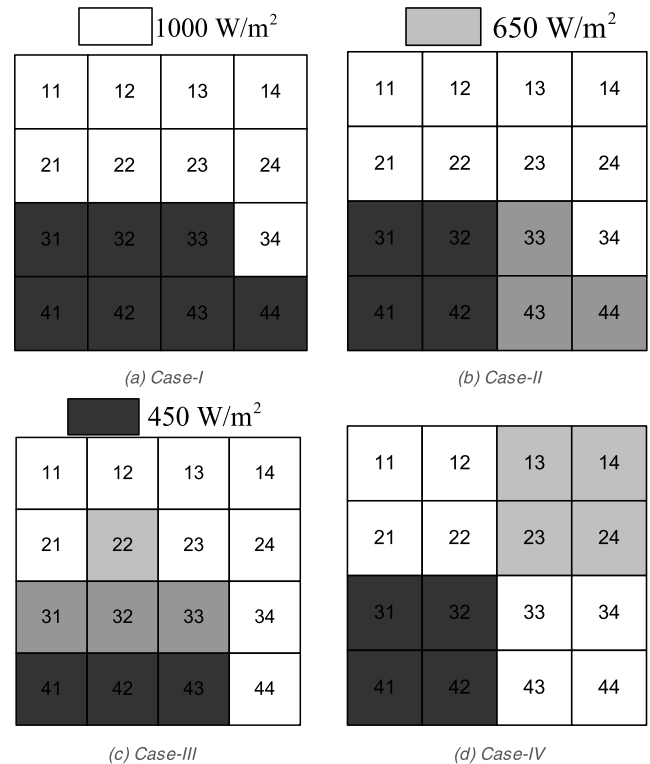


FIGURE 4. (a)-(d). Shading cases for performance investigation.

shaded PV modules is bypassed and improves system performance. Due to the shading effect, the MPP tracking techniques mislead to operate at the LMPP instead of the GMPP. Power losses due to PSCs are shown as characteristics of P - V and I - V shown in Fig. 3.

The maximum possible power under PSCs is the summation of the maximum power generated under the same level of irradiation by the individual PV module. Without shading effect, the maximum power generated by array is always higher than the power generated by PSC's, this difference leads to the shading loss and given in Eq. (4) as,

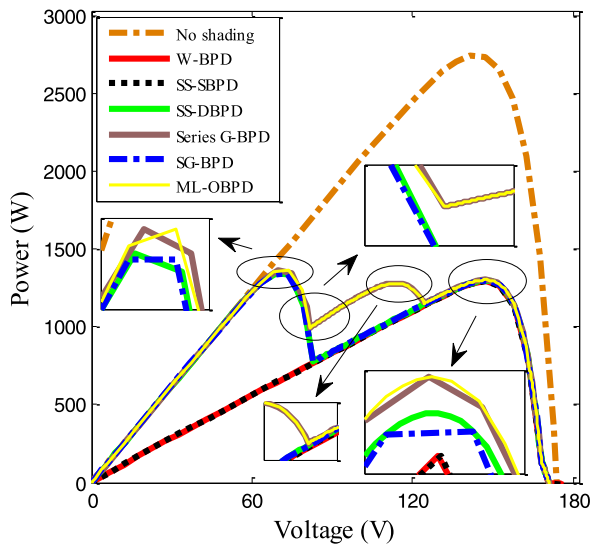
$$P_L = MPP_{ws} - GMP_{us} \tag{4}$$

where, P_L – power losses, MPP_{ws} – Maximum power without shading and GMP_{us} – GMP under shading.

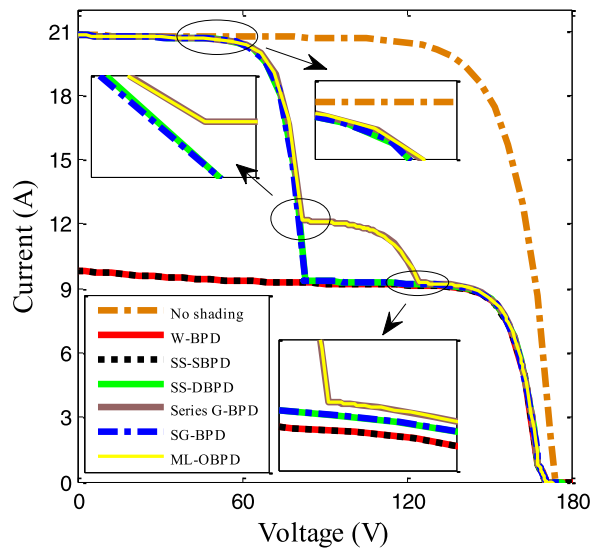
The considered shading cases are given in Fig. 4. The non-uniform shading conditions are clearly shown with distinguish irradiation levels as 1000W/m², 650W/m² and 450W/m².

V. RESULTS AND DISCUSSION

In the above section IV, four different shading patterns are presented to evaluate the performance of the proposed methods. In all BPD topology based PV array systems, the position of GMPP is theoretically calculated. The number of rows passed by to extract the maximum power. In the MATLAB/Simulink environment, the theoretical results are verified effectively.



(a)

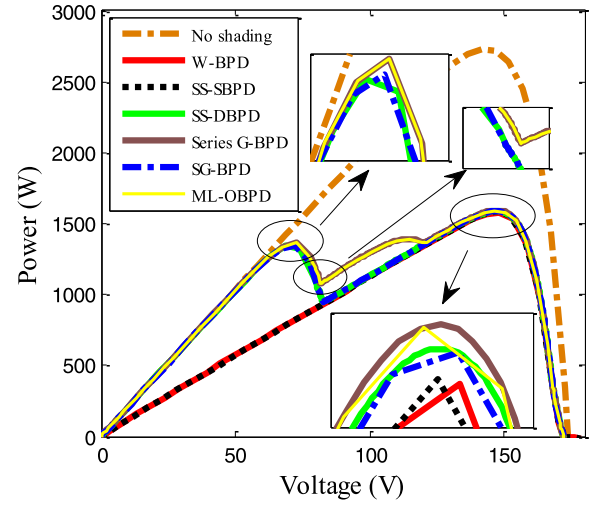


(b)

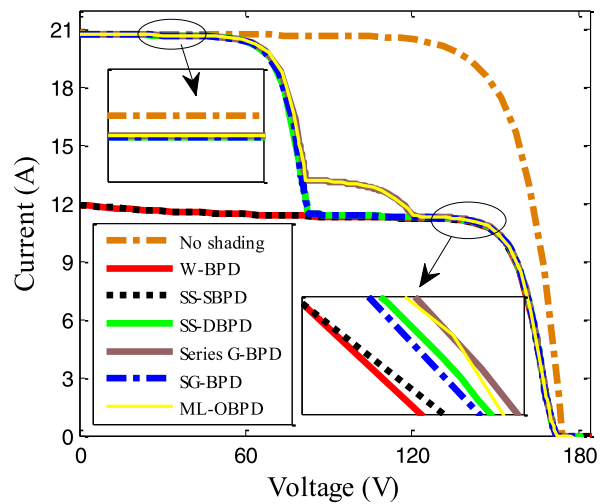
FIGURE 5. (a)-(b). P-V and I-V curves under shading case-I.

A. A PERFORMANCE ANALYSIS OF BPD METHODOLOGIES UNDER SHADING CASE-I

Under the shadow case-I, performance characteristics such as I-V and P-V curves are obtained with the different diode integration topologies as shown in Fig. 2(a)–(f). The performance behavior of the I-V and P-V curves is compared and the highest value of GMPPs is 1365W in the BPD topologies for the G-BPD and ML-OBPD series. The same topologies also have the minimum power losses. In addition, at higher voltage side such as 143.7V for W-BPD, SS-BPD topologies, maximum voltage (V_m) is found. In addition, another important parameter such as FF has the values of 0.77 for the topologies W-BPD and SS-BPD. Lastly, it is observed that under the shadow cases-I, the W-BPD, SS-BPD has low GMPP but it has smooth I-V and P-V curves (single GMPP existed). Which doesn't mislead the MPP tracking technique.



(a)



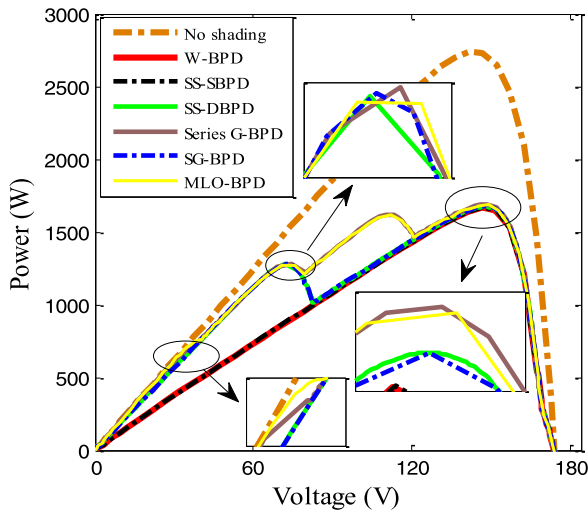
(b)

FIGURE 6. (a)-(b). P-V and I-V curves under shading case-II.

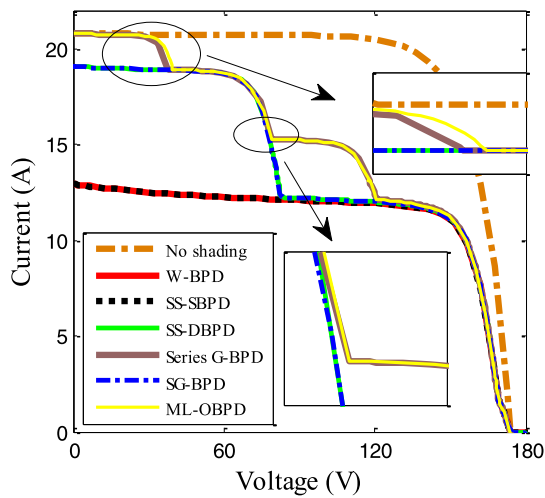
It is concluded under the shadow test case-4(a), G-BPD and ML-OBPD topologies have the best GMMP location performance, shown in Fig. 5.

B. PERFORMANCE ANALYSIS OF BPD METHODOLOGIES UNDER SHADING CASE-II

Performance characteristics such as I-V and P-V curves are obtained under the shadow case-II SP configuration with the different topologies of diode integration shown in Fig. 2(a)–(f). The performance behavior of the I-V and P-V curves is compared and the highest GMPP value and the minimum power loss for the G-BPD Series is 1598W and 1132W respectively in the BPD topologies. In addition, for W-BPD topology, maximum voltage (V_m) is found on the higher voltage side such as 148.4V. In addition, another important parameter such as FF, which has the SS-BPD topology values of 0.790. In the end, it is observed that under the shadow rest cases-II, the W-BPD, SS-BPD has low GMPP but smooth I-V and P-V curves (single GMPP existed). Which doesn't



(a)



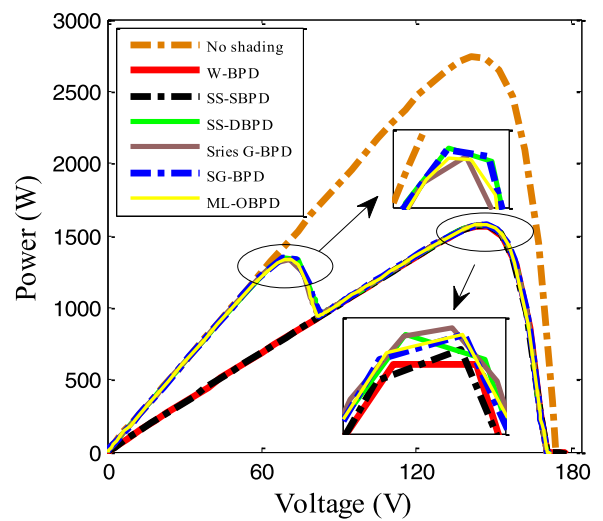
(b)

FIGURE 7. (a)-(b). P-V and I-V curves under shading case-III.

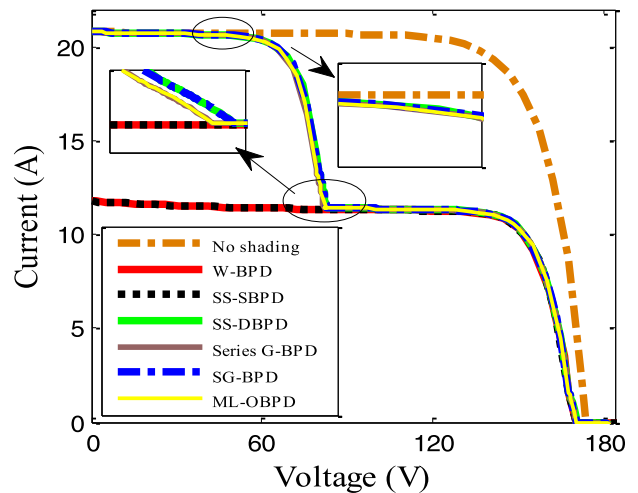
mislead the MPP tracking technique. It is concluded under the shadow case-II, Series G-BPD has the best GMMP location performance, shown in Fig. 6.

C. PERFORMANCE ANALYSIS OF BPD METHODOLOGIES UNDER SHADING CASE-III

Under the shadow case-III, performance characteristics such as I-V and P-V curves are obtained with the different topologies of diode integration as shown in Fig. 2(a)-(f). In the BPD topologies for the G-BPD series, the performance behavior of the I-V and P-V curves is compared and the highest value of GMPPs is 1686W. Both topologies in this sequence have minimal power losses. In addition, maximum voltage (V_m) is found on the higher voltage side such as 149.2V for ML-OBPD topology. Additionally, another important parameter such as FF has values of 0.765 for W-BPD and SS-BPD topologies. Lastly, it is observed that SS-SBPD has low GMPP under the shadow rest cases-III, but it has smooth I-V and P-V curves (single GMPP existed). Which does not mislead the



(a)



(b)

FIGURE 8. (a)-(b). P-V and I-V curves under shading case-IV.

MPP tracking technique. It is concluded under the shadow test case. The topology of ML-OBPD has the best performance in the higher GMMP location shown in Fig. 7.

D. PERFORMANCE ANALYSIS OF BPD METHODOLOGIES UNDER SHADING CASE-IV

Under the shadow case-IV, performance features such as I-V and P-V curves are obtained with the different diode integration topologies shown in Fig. 2(a)-(f). The performance behavior of the I-V and P-V curves is compared and the highest value of GMPPs is 1577W in the BPD topologies for the G-BPD series. The same topologies also had a minimum power loss of 242W. In addition, for SG-BPD and ML-OBPD topologies, maximum voltage (V_m) is found on the higher voltage side such as 147.4V. In addition, another important performance parameter such as FF, which has the SS-DBPD topology values of 0.815. It is observed that the W-BPD, SS-SBPD has low GMPP but it has a smooth nature of I-V and P-V curves (single GMPP existed) under the considered

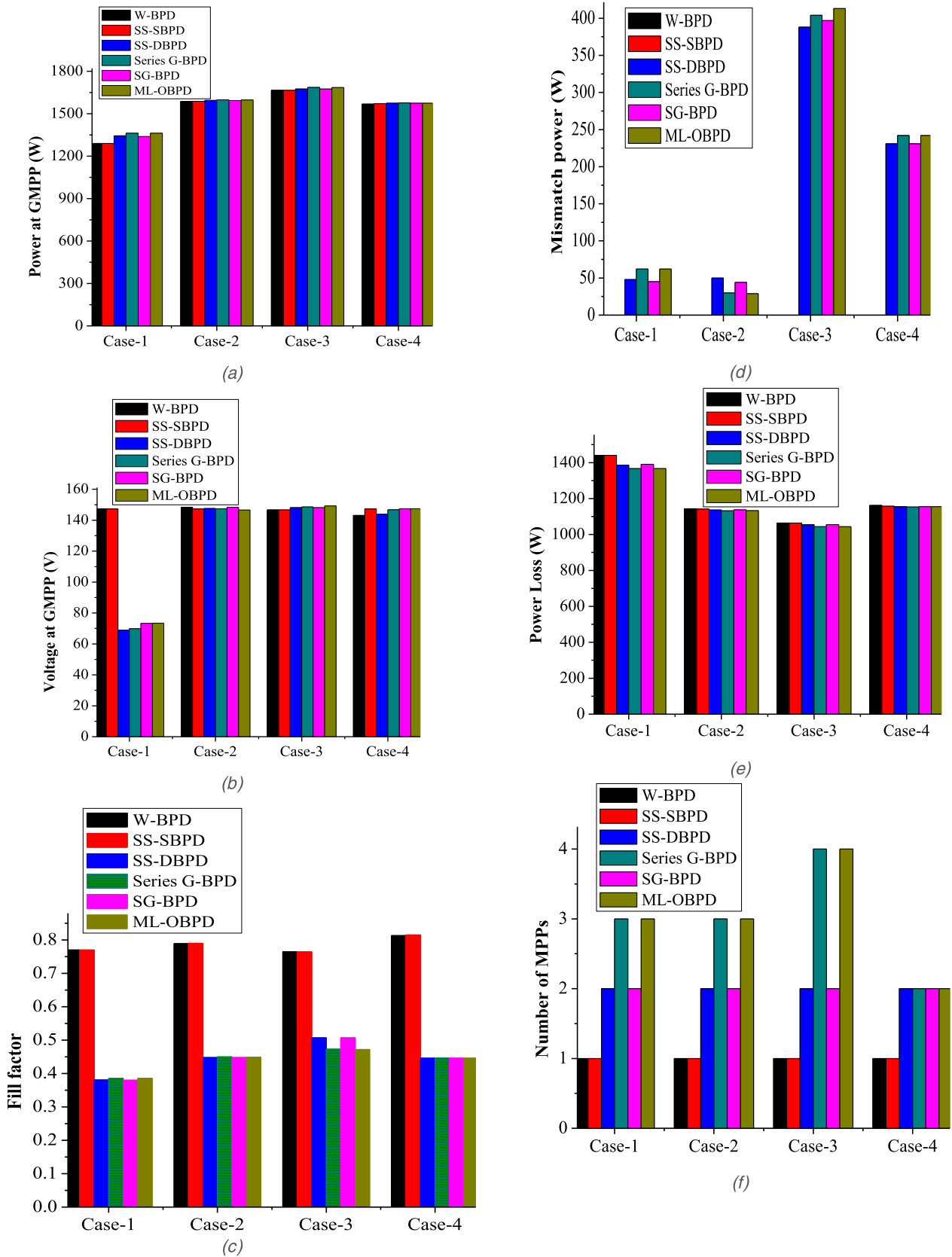


FIGURE 9. (a)-(f). Bar chart comparison of performance parameters.

TABLE 1. Performance Parameters of Considered BPD integrated PV Array systems under Shading Cases: I-IV.

Electrical parameters	W-BPD	SS-SBPD	SS-DBPD	Series G-BPD	SG-BPD	ML-OBPD	Shading cases
O. C. voltage (V_{OC}) (V)	169.9	169.9	169.9	169.9	169.9	169.9	CASE-I
S. C. current (I_{SC}) (A)	9.716	9.716	20.73	20.73	20.73	20.73	
Max. voltage (V_{max})	147.3	147.3	68.83	69.86	73.32	73.41	
Maximum current (I_m)	8.75	8.75	19.52	19.51	18.26	18.56	
Power at GMPP (W)	1290	1290	1344	1363	1339	1363	
Mismatch power (W)	0	0	48	62	45	62	
Power loss (W)	1440	1440	1386	1367	1391	1367	
Fill factor	0.77	0.77	0.381	0.386	0.380	0.386	
Number of MPPs	1	1	2	3	2	3	
Electrical parameters	W-BPD	SS-SBPD	SS-DBPD	Series G-BPD	SG-BPD	ML-OBPD	CASE-II
O. C. voltage (V_{OC}) (V)	171.2	171.2	171.2	171.2	171.2	171.2	
S. C. current (I_{SC}) (A)	11.73	11.73	20.73	20.73	20.73	20.73	
Max. voltage (V_{max})	148.4	147.3	147.6	147.4	148.3	146.6	
Maximum current (I_m)	10.69	10.78	10.79	10.84	10.74	10.89	
Power at GMPP (W)	1587	1588	1594	1598	1593	1597	
Mismatch power (W)	0	0	50	30	44	29	
Power loss (W)	1143	1142	1136	1132	1137	1133	
Fill factor	0.789	0.790	0.448	0.450	0.448	0.449	
Number of MPPs	1	1	2	3	2	3	
Electrical parameters	W-BPD	SS-SBPD	SS-DBPD	Series G-BPD	SG-BPD	ML-OBPD	CASE-III
O. C. voltage (V_{OC}) (V)	173.5	173.5	173.5	173.5	173.5	173.5	
S. C. current (I_{SC}) (A)	12.54	12.54	18.99	20.53	18.99	20.53	
Max. voltage (V_{max})	146.7	146.7	148.1	148.6	148.1	149.2	
Maximum current (I_m)	11.35	11.35	11.30	11.34	11.30	11.29	
Power at GMPP (W)	1666	1666	1675	1686	1675	1685	
Mismatch power (W)	0	0	388	404	397	413	
Power loss (W)	1064	1064	1055	1044	1055	1045	
Fill factor	0.765	0.765	0.507	0.473	0.507	0.472	
Number of MPPs	1	1	2	4	2	4	
Electrical parameters	W-BPD	SS-SBPD	SS-DBPD	Series G-BPD	SG-BPD	ML-OBPD	CASE-IV
O. C. voltage (V_{OC}) (V)	169.8	169.8	169.8	169.8	169.8	169.8	
S. C. current (I_{SC}) (A)	11.35	11.35	20.76	20.76	20.76	20.76	
Max. voltage (V_{max})	143.1	147.3	143.8	146.8	147.4	147.4	
Maximum current (I_m)	10.95	10.67	10.95	10.74	10.68	10.68	
Power at GMPP (W)	1568	1572	1575	1577	1575	1575	
Mismatch power (W)	0	0	231	242	231	242	
Power loss (W)	1162	1158	1155	1153	1155	1155	
Fill factor	0.813	0.815	0.446	0.447	0.446	0.446	
Number of MPPs	1	1	2	2	2	2	

shadow rest case. Which doesn't mislead the MPP tracking technique. It is concluded under the considered shadow test case, Series G-BPD topology has the best performance in terms of higher GMPP location, as shown in Fig. 8.

For the extensive comparative study, statistical analysis of performance parameters such as power-voltage generated at GMPPs, FF, mismatch power, minimum power losses and number of MPPs is performed. The parameters considered are taken for all shading cases-I-IV. The bar graphs of all performance parameters are shown in Fig. 9(a)-(f) to show the comprehensive comparative study and quantitative performance parameter values are shown in Table 1, as shown below.

VI. CONCLUSION

In this article, under the four distinctive shadow test cases: I-IV, a MATLAB/Simulation is performed for the performance assessment of BPD placement topologies in SP configured PV array system. The salient points of study are as follows,

- In shading test case -I: GMPP power is obtained as 1363W and power losses are minimized as 1367W for the topologies of the Series G- BPD and ML-OBPD.
- In shading case-II: GMPP power is obtained as 1598W and power losses for the G-BPD Series are minimized as 1132W.

- In shading case - III: power at GMPP is acquired as 1686W and power losses are minimized as 1044W for the G-BPD series.
- In shading test case- IV: power at GMPP is acquired as 1577W and power losses are minimized as 1153W for the G-BPD series.
- In terms of the number of MPPs, W-BPD and SS- SBPD have only one MPP compared to other topologies. Moreover, in all shading cases, these same BPD topologies have higher FF (case-I: 0.77 and 0.77; case-II: 0.789 and 0.790; case-III: 0.765 and 0.765; case-IV: 0.813 and 0.815).
- Overall, concluded that the G-BPD Series topology has a maximum GMPP value for almost cases of considered shading.

The obtained results confirm the impact of shading phenomenon for performance validation of PV systems with BPD topologies.

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