

Modified Series-Parallel Photovoltaic Configuration to Enhance Efficiency under Partial Shading

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Abstract: Partial shading is a phenomenon where photovoltaics (PV) array experiences irregular level of irradiances. Such mismatch can cause a significant reduction in power yield. To mitigate the effect of partial shading, PV modules in an array are connected in various configurations namely Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Linked (BL) and Honey-Comb (HC) etc. However, all these techniques introduce redundancy and complexity while improving the performance by very little. In this paper, a new PV configuration is proposed to solve the limitations of the existing PV configurations. The proposed configuration is a modified version of SP, hence referred as MSP configuration. To justify the performance of the proposed scheme, several experiments have been carried in MATLAB Simulink. Total 14 partial shading cases are simulated to compare the output performance between generic SP and proposed MSP configuration. The proposed MSP configuration is validated to be superior compared to normal SP configuration under majority of the cases. Depending on shading pattern, the efficiency of the PV array can be enhanced up to 37%, if MSP configuration is implemented.

Keywords: Solar, PV configuration, Partial Shading, SP configuration, Maximum power

1. Introduction

Due to the rapid depletion of fossil fuel along with the concern for environmental issues, the usage of renewable energy such as solar power has increased drastically for the past few decades. As the implementation of PV systems is soaring high throughout the world, energy loss due partial shading remains as a big concern [1]. It is extremely laborious to enhance the efficiency of the system especially at places like urban areas where there are cloud movements, shadows of high rise buildings, transmission towers, high poles, tall trees or anything which may blocked the sunlight [2]. To mitigate the effect of partial shading either intelligent maximum power point tracker (MPPT) or different PV configurations are usually deployed [3, 4]. In this work, we have focused on different PV configuration and aimed to provide a better solution.

According to [5, 6], different configurations of PV modules such as Series-Parallel (SP), Bridge-Linked (BL), Honey-Comb (HC) and Total-Cross-Tied (TCT) configurations has been implemented in order to enhance the efficiency of existing PV systems. Nonetheless, there are certain advantages and deficiencies of using these PV modules configurations in which to some extent, some of the PV configurations may perform well at certain partial shading scenarios and, vice versa. Fig.1(a) shows the schematic diagram of a (4×4) SP configuration. The SP configuration is consisting of parallel of series strings of PV cells. This is the most common PV configuration which is applied worldwide. However, such configuration is the most vulnerable under partial shading [7, 8]. In SP current flows through individual strings, thus one affected module hampers the whole string. To counter such limitation TCT, as presented in Fig. 1 (b), is a better performing configuration which provide multiple alternative pathways for the current to flow [9]. However, based on the results obtained by [10], SP configuration can still perform better to TCT when comes to string shading. In other cases, cross wirings throughout all PV modules in TCT provides alternative paths for current flow which leads to better performance [11]. Nevertheless, TCT requires numerous wirings in large scale PV implementation where wiring loss can be significant and installation cost is higher. Thus, two other configuration (4×4) Bridge-Linked (BL) and Honey-comb (HC) is presented in the literature [12]. In BL an HC wiring connection is reduced compared to TCT, although efficiency is very close to the TCT [13]. Thus, BL and HC are more economical than TCT which reduce the implementation costs [14]. Besides, less wiring connection also leads to less maintenance, corrosion possibility, wiring malfunctions etc. Such advantages improves the operational lifetime [15].

In another work [16], a zigzag based PV configuration is proposed. Though quite effective in small scale PV arrays, complexity introduced through it is unfavorable for large scale PV. In different works, Sudoku based PV configuration and reconfigurable scheme is proposed [17, 18]. In these schemes, some part of the PV array is remaining fixed and some parts are flexible to be reconfigured through many switches. The fundamental idea is to keep the string currents almost equal. However, such schemes require intelligent programming and complex circuits with many switches. Thus, these methods are usually not implemented in consumer level.

Due to such limitations of the different PV configurations, Normal SP is still the most prominent and popular configuration for practical implementation. Even in MPPT and PV converter/inverter researches, researchers consider the normal SP configuration as reference for developing new MPPT techniques and design the converter/inverter. Thus, this work analysed the behaviour of the normal SP configuration thoroughly and modify the arrangement of PV modules intelligently so that the overall performance is improved. The proposed configuration is name modified SP (MSP) throughout the paper. The proposed MSP scheme and normal SP is subjected to 14 different shading patterns which is quite extensive. Simulation results suggest that the MSP configuration is better in terms of efficiency, wirings and complexity compared to normal SP configuration.

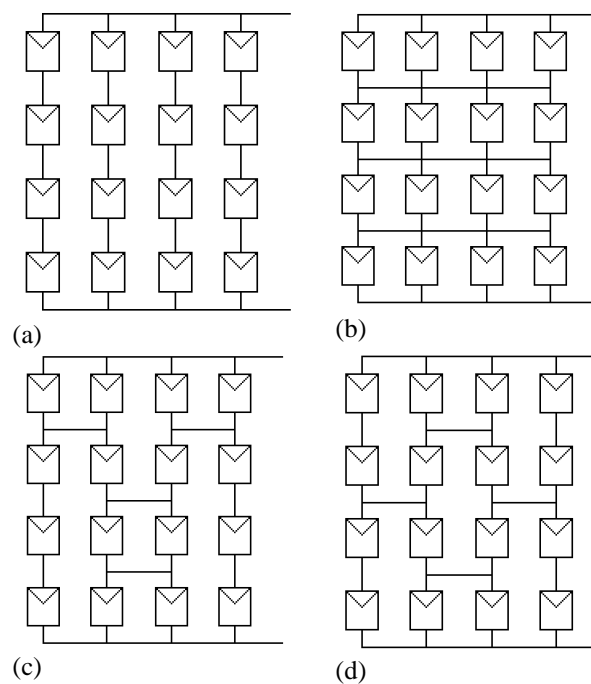


Fig. 1- Various PV configurations (a) SP, (b) TCT, (c) BL, (d) HC

2. Behaviour of Normal SP under partial shading

To understand the behavior of SP configuration under partial shading, two shading scenarios are presented in Fig. 2. In Fig. 2 (a), shading is on the left side and hence one string is affected. However, in Fig. 2 (b), same shading pattern is approaching from the bottom and thus three strings are affected. As can be seen in the P-V curve, the power yield for side shading is 3362 W, while for bottom shading is 2908W. Through that observation a conclusion can be drawn as if shadow affects more strings of the array, power reduction is higher. This same observation is also verified in [10] through simulation and hardware results.

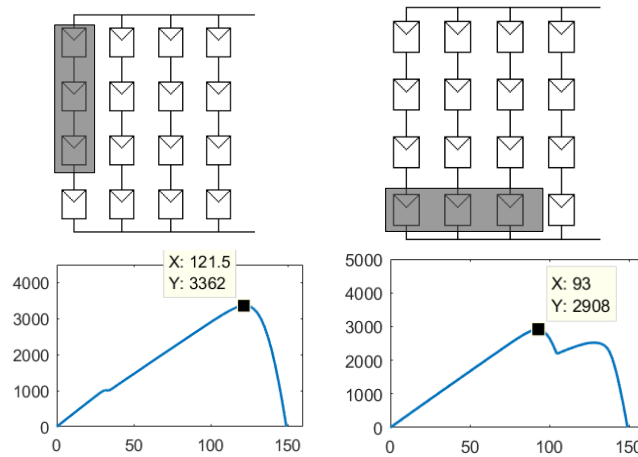


Fig. 2 - Effect of different shadow positions on SP configuration

Due to such behavior of SP configuration, this work presents a new configuration name Modified SP (MSP) as presented in Fig. 3. This is also the same as generic SP configuration. However, strings are positioned on the corner of configuration. Due to the such positioning, in majority of the cases shadows will be concentrating on one string rather than gets distributed in multiple string.

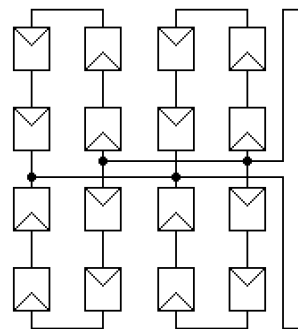


Fig. 3 - Proposed MSP configuration

Such claim is evident from the 14 cases presented In Fig. 4. In Case 1 & 2, shadow is approaching from the side. In case 1, generic SP in a better position since one string is affected. In MSP, two strings are affected because shadow gets distributed. In case 2 both SP and MSP have two strings affected. However, when shadow approached from the top in case 3 & 4, four strings are affected in SP while only two string got affected in MSP. This gives MSP a clear advantage to produce more power. In case 5 & 6, shadow is approaching from the corner. In these two cases, strings in SP are affected as two and four while in MSP affected strings are one and three only. In case 7 & 8, both SP and MSP got three strings affected. However, MSP will perform better compared to SP, since in MSP one full string is affected and other two strings are affected by two module and one module. On the contrary in SP, two strings got 3 modules affected and the other one got two modules affected. In case 9, both SP and MSP will perform the same as two modules in each four strings got affected. However, in case 10, shadow is concentrated in the middle. Thus, in SP only two strings are affected while in MSP four strings are affected. Thus, SP will perform better.

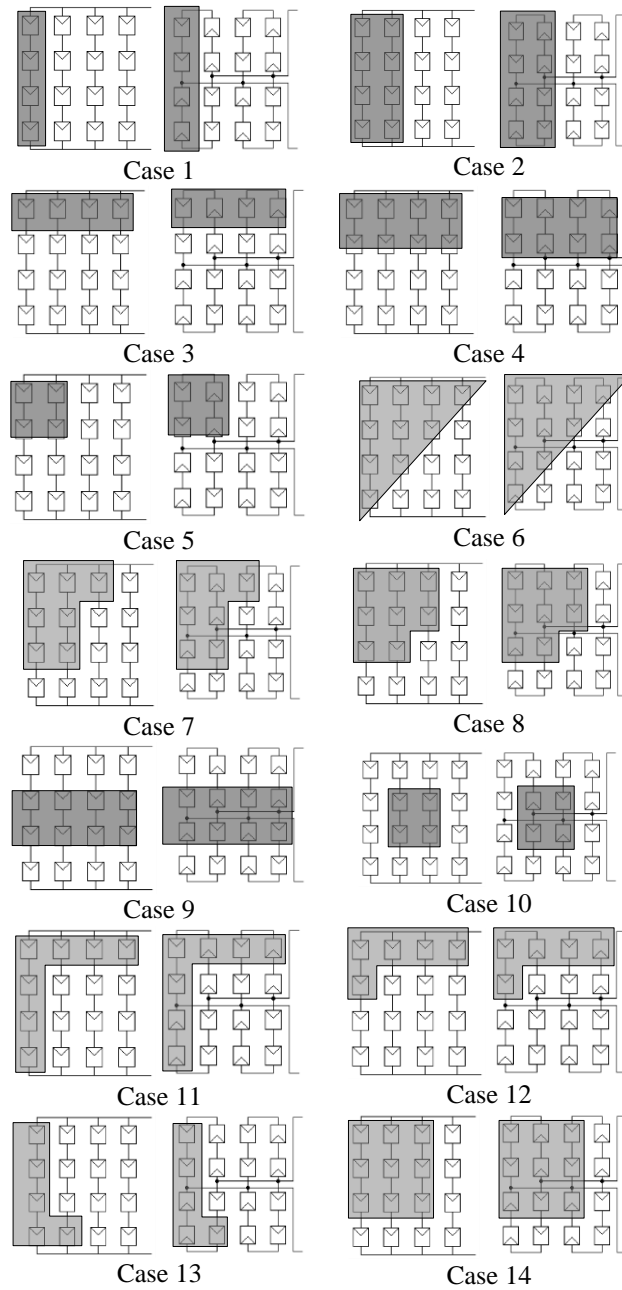


Fig. 4 - Fourteen different partial shading cases

In case 11, shading is approaching from both side and top evenly. In SP, four strings are affected while in MSP, three strings are affected. Consequently, MSP is expected to provide more power. However, a closer look shows that, in SP one full string is shaded and other three strings have one module shaded each. Thus, the shadow is concentrated mainly on one full string. On the other hand, in MSP shadow is heavily distributed in three strings. Thus, SP is expected to perform better.

In case 12, since four strings are affected in SP and only two strings are affected in MSP, it can be expected that MSP will be providing more power. On the other hand, shading cases 13 & 14 are favorable for SP. Although in 13, both SP and MSP have two affected string. However, in SP shading is concentrated in one complete string and one module from another string. In MSP, shadow is distributed and thus it is expected to perform worse. In case 14, only three strings are affected in SP, but in MSP four strings are affected. Thus, SP should perform better.

In comparison, as summarized in Table 1, MSP will perform better than generic SP in 7 cases, in 2 cases performance will be same and SP will be better in 5 cases. Thus, MSP can be considered as a better choice compared to generic SP. Their performances under these 10 different cases are analyzed numerically in the result section.

Table 1- Affected strings in SP and MSP under shadow cases 1-14

	Strings affected under shading cases 1-14													
Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SP	1	2	4	4	2	4	3	3	4	2	4	4	2	3
MSP	2	2	2	2	1	3	3	3	4	4	3	2	2	4

3. Simulation Results in Simulink

PV modules in Matlab is connected in proposed configuration to simulate the shading cases. One sample circuit is presented in Fig. 5.

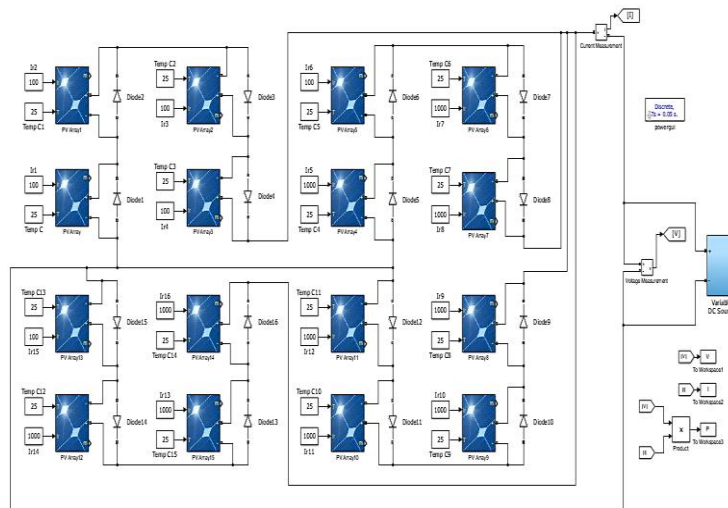


Fig. 5 - Proposed MSP configuration in Simulink

Samsung SDI LPC235 PV Modules are chosen for the simulation. Rating of PV module is as follows. $V_{oc} = 37.24$, $I_{sc} = 8.43A$, $V_{mpp} = 29.97 V$, $I_{mpp} = 7.84 A$, $P_{max} = 235 W$. Modules are connected in a 4x4 configuration as presented in shading cases. All modules are connected with bypass diodes to avoid hotspots due to partial shading. The shading irradiance is $500 W/m^2$ while unshaded irradiance is $1000 W/m^2$. To maintain the uniformity, temperature is kept at $25^{\circ}C$ for all modules. The whole PV array is externally connected to a variable DC source which works as a voltage regulator. This DC source, increment the voltage from 0 to open circuit voltage of the PV array which is $4 \times 37.24 = 149 V$. Throughout the increment, output current and power from the PV array is recorded. Finally, P-V curve is plotted in Matlab and maximum power (P_{max}) is recorded for all 14 shading cases.

3.1 Results & Discussions

The simulation results of the 14 shading cases for both SP and MSP is presented in Fig. 6. Maximum power attainment P_{max} in SP and MPS are recorded in Table 2 and presented as a bar chart in Fig. 7. Along with that, the enhancement done by MSP is calculated in table 2 as follows.

$$enhancement(\%) = \frac{P_{max,SP} - P_{max,MSP}}{P_{max,SP}} \times 100 \quad (1)$$

In calculating the enhancement, P_{max} in SP is considered as the base since this is the presently implemented system worldwide. Thus, how much improvement can be attained through MSP is easily demonstrated based on the power attainment in normal SP.

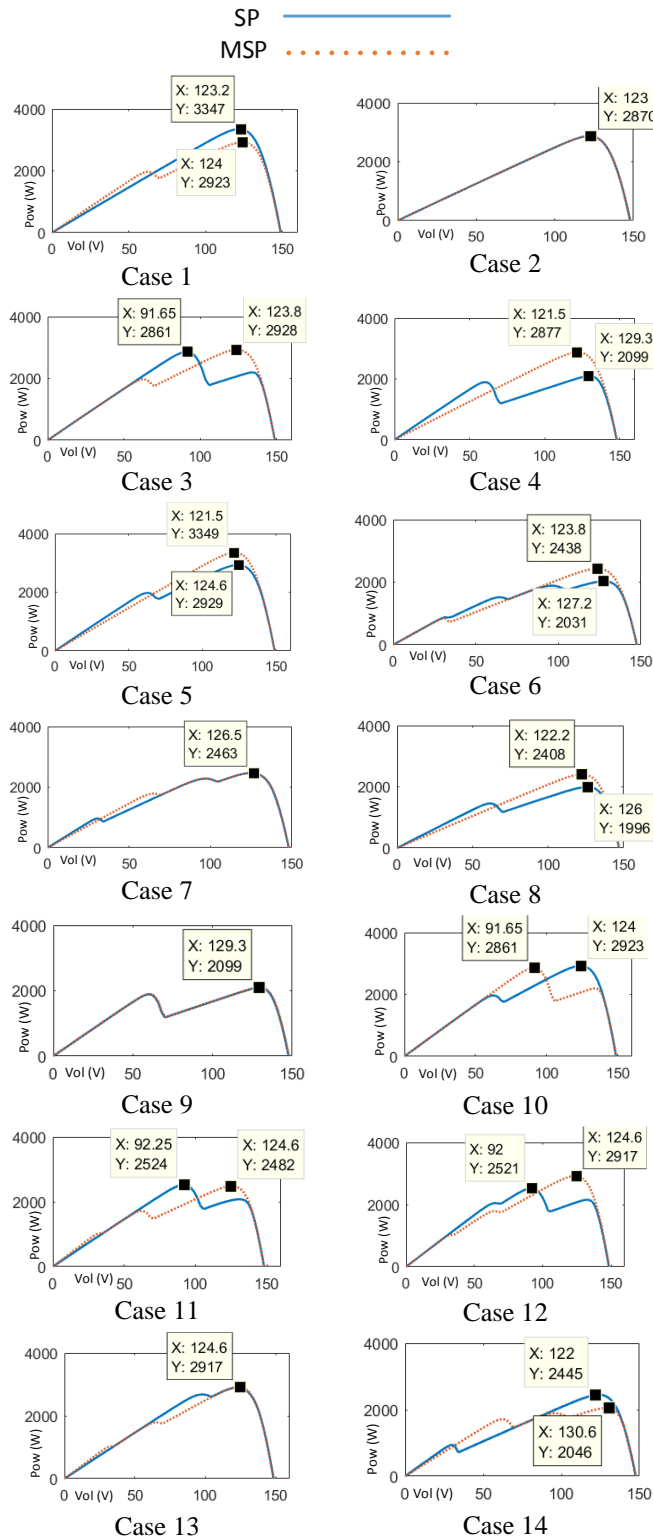


Fig. 6: Simulation results for fourteen cases

From the simulated result, it can be seen that the physical investigation in section 2 is highly accurate. SP is performing better in case 1. Since shadow is approach from the side, one complete string is affected under SP. Meanwhile, in MSP shadow is distributed in two strings. In case 2, both SP and MSP is performing equally, since two strings from each is shades. In case 3, Shadow is approaching from the top side. Thus, in SP four strings are affected. On the other hand, in MSP only 2 strings are affected. Consequently, MSP produces more power and enhancement is about 2.34%. Under case 4, a significant enhancement in energy yield is noticeable. In SP, four strings are affected while in MSP two strings are shadowed. Consequently, power yield is increased up to 37.06%.

In case 5, shadow is approaching from the corner. Thus, two strings are affected in SP and only one in MSP. Due to that, MSP performs better and produces 14.40% more power than SP. In case 6, a larger portion of shadow is approaching from the corner. Consequently, four strings are affected in SP and three strings in MSP. As a result, MSP produces, 20.04% more power than SP. In case 7 & 9, SP and MSP performing the same and produces same amount of power. However, supremacy of MSP is again demonstrated by enhancing the yield by 20.64%. Though both SP and MSP is affected by 3 strings, in MSP, shadow is concentrated in one full string and slightly affecting other two. On the other hand, 3 strings are deeply shaded and thus performing poorly.

Case 10 & 11 is favorable for SP. More strings are affected in MSP compared to SP. However, power yield difference is not very high. It is 2.12% and 1.66% respectively. Under case 12, MSP regain its better performance. It produces 15.70% more power than SP, since shadow is affecting only two strings. While, shadow is affecting 4 strings in SP. In case 13, both SP and MSP is producing same maximum power. Although their local peak positions are different. In final case, SP is performing better significantly. It produces 16.32% more power than MSP. The reason is easy to notice. In MSP four strings are affected while in SP, shadow is affecting only three strings.

In comparison SP is performing better in case 1, 10, 11 and 14. On the other hand, MSP is providing more power in case 3, 4, 5, 6, 8, and 12. In case 7, the power attainment for SP and MSP is same. However, MSP can be considered better since there are only 2 local peaks are generated while SP exhibited 3 local peaks. Under case 2 & 9, performance of SP and MSP is the same as predicted earlier. Under case 13, SP will be considered better since it has created 2 local peaks while MSP produced 3 local peaks. Thus, in numerical counting, MSP is better in 7 cases while SP is better in 5 cases and under 2 cases performance is exactly the same. Consequently, MSP has performed better than SP if overall results are considered.

However, the real advantage of MSP can be seen from the enhancement numerals. In case 10 & 11, MSP produced less power than SP but the difference is very low. Only in case 1 & 14, SP produce significantly more power than MSP which is 12.66 % and 16.32 % respectively. On the contrary, the exhibited better performance by MSP is quite significant in several cases. As recorded in table 2, in case 4, 5, 6, 8 and 12, the improvement done by MSP is 37.06%, 14.40%, 20.04%, 20.64% and 15.70% respectively. In contrast to SP, these enhancement percentage is quite high. Consequently, considering the long-life span of PV modules, MSP is expected to enhance the overall efficiency of the PV system by a significant margin.

Table 2 - Maximum power attainment (P_{max}) in SP and MPS

Cases	P_{max} in SP (W)	P_{max} in MSP (W)	Enhancement (%)
1	3347	2923	-12.66
2	2870	2870	0
3	2861	2928	2.34
4	2099	2877	37.06
5	2929	3349	14.40
6	2031	2438	20.04
7	2463	2463	0
8	1996	2408	20.64
9	2099	2099	0
10	2923	2861	-2.12
11	2524	2482	-1.66
12	2521	2917	15.70
13	2917	2917	0
14	2445	2046	-16.32

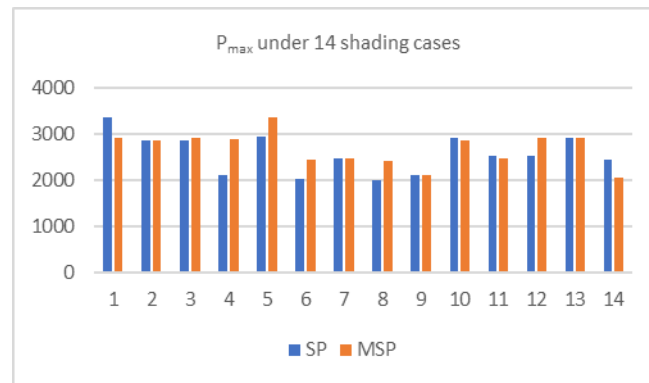


Fig. 7 - Maximum power attainment in SP and MSP under 14 shading cases.

3.2 Future Works

It is evident from the simulation results that MSP is a better choice compared to traditional SP as a PV configuration. However, this study is limited to a 4×4 symmetrical PV configuration. The performance of MSP under asymmetrical PV configurations should be investigated in the near future and more conclusive decision can be made. Besides, the performance of MSP should be benchmarked with other prominent PV configurations i.e. TCT, BL, HC etc. Moreover, the obtained simulated results should be verified through hardware implementation. Currently, such work is being carried out and verification from the hardware implementation will be reported in the literature very soon.

4 Conclusion

This paper has proposed a smart modification of the normal SP PV configuration and thus enhance the output efficiency. The proposed MSP configuration has the same inter module connection like normal SP but PV modules are intelligently placed in such a way that shadows get concentrated on strings. Due to such positioning, output power yield is improved significantly. In total 14 shading conditions has been tested and the simulation results validated that the MSP performs better than normal SP under majority of the conditions. On top of that, the output power can be enhanced upto 37% depending on the shading cases. Thus, it is envisaged that if MSP configuration is implemented instead of normal SP, then overall efficiency of PV system will be improved significantly throughout the total life span.

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