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PERFORMANCE ANALYSIS OF DIFFERENT PV ARRAY CONFIGURATIONS UNDER PARTIAL SHADING CONDITIONS

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Abstract-
Photovoltaic (PV) systems frequently experience partial shading, which has a substantial negative effect on the overall efficiency and performance of solar arrays. Precise knowledge of the affect of shading on the PV panels for a particular site is desired for accurate techno-economic analysis. The overall efficiency PV array is severely impacted under the partial shading conditions due to mismatch of power outputs from individual panels. In addition to having an intense nonlinear effect on power, partial shading exhibits multiple maximum power points on P-V and I-V characteristics, referred to as the local maximum power point and global maximum power point. Their efficiency under shading conditions can be improved by employing several methods such as PV array configurations, PV system architectures, MPPT techniques, and converter circuit topologies.
In this paper, the performance of various PV array configurations under partial shading conditions has been examined. PV array configuration is based on several electrical interconnection strategies used between PV modules. The considered photovoltaic array configurations are Series, Series-Parallel, Total-Cross-Tied, Bridge-Link, and Honey-Comb. Each array configuration is simulated under various partial shading patterns such as Short and Narrow, Short and Wide, Long and Narrow, Long and Wide, and Diagonal shading patterns. The above-mentioned configurations of 5x5 PV array were simulated and their performance were analyzed under standard test conditions and different partial shading patterns. The objective of the analysis was to assess the best array configuration under the shading pattern. The selected PV module for this work was KYOCERA SOLAR KC200GT. The best PV array configuration is determined for each shading pattern based on the computation of shading loss (P_S), mismatch power losses (ΔP_L in %), performance ratio (PR in %), and fill factor (FF). From the simulation results it was observed that under all shading conditions, the T-C-T configuration outperformed than all other configurations.

1 INTRODUCTION

Exploring new methods of energy generation has become necessary due to the ever-increasing energy demand pushed by population growth, technological advancements, industrial expansion, and environmental concerns. Consciousness about global warming, greenhouse effects, and the depletion of natural resources like fossil fuels, natural gas, and coal are driving research into technologies that can harvest energy from renewable energy sources like wind, solar, tidal waves, etc. Among all other renewable energy sources, solar energy is one that is frequently employed to address the energy demand. Application solar energy is growing rapidly because of its abundance, sustainability, and accessibility. Even though solar energy has several benefits, it also has certain drawbacks, such as partial shading effect. With a physical SPV module, it is difficult to study the effects of partial shading since field testing is costly, time-consuming, and depends heavily on the prevailing weather conditions. However, it is convenient and easier to carry out the study of partial shading through simulations.

The main design objective of solar photovoltaic (*SPV*) systems is to extract the maximum power from the PV systems for a long time. The amount of power extracted from the PV array can be affected by temperature, solar irradiation, dust accumulation, PV array configuration, and shading pattern. In general, the variations in solar irradiation due to partial shading is considered as the prominent factor affecting the *SPV* generation [1].

As solar PV systems become more integrated into the energy grid, optimizing power generation from *SPV* arrays is crucial, especially in partial shading conditions. Partial shading occurs when parts of a PV array are shaded, resulting in decreased output power. It can lead to power loss, hot-spotting, mismatch losses, and reduced energy production, impacting overall system efficiency and extending the panel's payback time. This also affects panel lifespan due to local hotspots on the PV panels. These losses can be minimized by using different PV array configurations, system architectures, MPPT techniques, and converter circuits. Among these, optimizing PV array configurations is the most effective approach. It is based on several electrical interconnection strategies used between PV modules [2].

The paper as organized as follows:

Introduction in section 1 is followed by literature survey of the various studies carried out in the past on the affects of partial shadow on SPV panels. Section 3 contains the overview of the methodologies adopted for assessing the shadowing affect on solar panels. Results and discussions are presented in section 4 and finally the conclusions of the study are given in section 5.

Several researches carried out in the past have investigated the affect of different PV array configurations in handling the partial shading issues. A module of size 3x3 made of series (S), parallel (P), series-parallel (SP), bridge-linked (BL), total-cross-tied (TCT), and honeycomb (HC) was created to evaluate the impact of solar PV modules under partial shading. Results compared open-circuit voltage (OCV), short-circuit current, global maximum power point (GMPP), local maximum power point (LMPP), v-i characteristics, and assessed mismatching power losses, fill factor efficiency, and power productivity. Findings showed that mismatching power loss increases with more series connections but significantly decreases with the inclusion of bypass diodes [3].

These studies examined partial shading losses in different solar module connection configurations under non-uniform illumination. Using MATLAB, various setups were tested, including Simple Series (SS), Series-Parallel (SP), Total-Cross Tied (TCT), Bridge-Linked (BL), and Honey Comb (HC), all with bypass diodes to prevent hotspots. The findings indicate that SP and HC module configurations are more susceptible to power losses than other configurations in non-uniform irradiation and shading conditions [4].

Using a one-diode model in MATLAB/Simulink, this study examined the performance of different PV array configurations aimed at minimizing the impact of partial shading. Various setups, including parallel-series, honeycomb, linked-bridge, total cross-tied (TCT), and an optimized TCT (OTCT) layout, were evaluated under different scenarios. Comparing the simulated power generation of each configuration revealed that the OTCT configuration outperforms the others. It consistently delivers higher power output with lower losses, resulting in superior electrical performance [5].

The study investigated the impact of different shading patterns on solar power curves and spatial shading on PV panels using MATLAB. Various parameters, including PMP, VOC, ISC, VMPP, IMPP, PL, and FF, were analyzed. Simulation results with 16 Kyocera solar panels validated the findings. In summary, the Series configuration performed better in short and narrow shadowing conditions, while the Series-Parallel design outperformed in short and broad, long and narrow, and long and wide shading scenarios. Surprisingly, the Total Cross Tied solar model excelled mainly in short and narrow shadowing conditions, making it a promising choice for universal shading scenarios [6].

A study analyzed the performance of various PV arrays under different shading scenarios, using a 6x6 PV array and four configurations: "Series" (S), "Series-Parallel" (SP), "Total-Cross-Tied" (TCT), and "Bridge-Link" (BL). The modeling was done in Matlab/Simulink, comparing their output characteristics and highest power output. The results revealed that the Total-Cross-Tied configuration consistently provided the highest maximum power output compared to the other configurations [7].
In the analysis of five different PV array configurations (series, series-parallel, total cross-tied, bridge link, and honeycomb) under various shading scenarios with a 5X5 PV array, using KC200GT PV module parameters simulated in MATLAB/Simulink, several factors were considered, including maximum power, shading loss (SL), mismatch loss (ML), and fill factor (FF). The findings revealed that all array layouts generated the same maximum power in uniform irradiation conditions. However, in partial shading conditions, PV array performance decreased. Among the configurations, the Total Cross-Tied (TCT) design consistently exhibited the best performance, showing the lowest shading losses, mismatch losses, and the highest fill factor and maximum power output across different partial shading scenarios [8].

2. LITERATURE REVIEW

This section deals with the overview of the previous research works performed in the field of partial shading affects on SPV systems. The research works presented below are helpful in comprehending the concepts of SPV systems and shading on the PV panels.
Saiprakash et al. (2021) proposed a new array configuration named Alternative Tri Tie (ATT). For performance comparison, a PV array of size 6x6 is modeled in MATLAB Simulink. Under PSC, PV modules experience a mismatch in power generation and exhibit uneven PV characteristics. The performance of ATT array configurations is examined in this study using 6x6 array configurations. Under various PS situations, the performance of the ATT configuration is compared to that of traditional array topologies. By selecting an appropriate PV array arrangement, the partial shadowing effect on the PV system can be minimized. Under varied shading situations, various PV configurations including S-P, B-L, T-C-T, H-C, and alternative tri tie (ATT) are taken into consideration. In terms of voltage at maximum power (V_m), current at maximum power (I_m), maximum power (P_m), and fill factor, the performance of various array configurations is analyzed. The Alternative tri-tie (ATT) design offers the best performance under all shading situations, according to a comparison of all array configurations in terms of maximum power and fill factor.
Pradhan and Kar (2020) examined the effects of various patterns, such as short narrow, short wide, long, and narrow, on the power curve of PV system and the spatial shading patterns on the PV panel. MATLAB software is used to analyze and implement parameters of different configurations, including Maximum Power (PMP), Open Circuit Voltage (V_{OC}), Short Circuit Current (I_{SC}), Maximum Power Point Voltage (VMPP), MPP Current (IMPP), Change in Power Loss (P_L), and Fill Factor (FF). The results were validated using simulation design and implementation for 16 Kyocera solar KD325GX-LPB solar panels. According to the results, it can be seen that the Series model is able to follow MP in better way than its competitors under short and narrow shadowing conditions. Under short and broad, long and narrow, and long and wide shading situations. The Series-Parallel design can extract more power than the Series Array configuration. However, the T-C-T solar model could not achieve MP, with the exception of short and narrow shadowing effects. The T-C-T Solar arrangement may therefore be more suitable for attaining the MP under a universal shading model than other state-of-the-art configurations.
Nadia et al. (2019) used a one-diode model in MATLAB/Simulink, to examine the functioning of various PV array configurations where PV modules can be placed in different ways to reduce the PS impact. This assessment is carried out by contrasting the results of various configurations and arrangements under various scenarios. Parallel-series, H-C, linked-bridge, T-C-T, and an optimal T-C-T layout have all been studied configurations. Comparing the amounts of power generated by each scheme on the basis of simulation results it was demonstrated that the OTCT configuration performed

better than the other schemes. OTCT often offers more power and lower losses, resulting in higher electrical performances.
Maharana et al. (2020) used five alternative array configurations, including series, series-parallel, T-C-T, B-L, and H-C, for analysis. Using a 5X5 PV array, six cases of shadowing situations were taken into consideration. The KC200GT PV module parameters was used and simulated in MATLAB/Simulink for PV array modeling. Maximum power, shading loss (SL), mismatch loss (ML), and fill factor (FF) were all been taken into account while analyzing the PV array's performance. The results showed that all defined array layouts delivered the same amount of maximum power under conditions of uniform irradiation. However, each PSCs resulted in decreased PV array performance due to the PSCs. The TCT design provides the best performance under all shading conditions, according to an analysis of the various PSCs and a comparison of all configurations' shading losses, mismatch losses, fill factor, and maximum power.
Deshpande and Bodkhe (2017) investigated the various partial shading losses on various solar module connection configurations under non-uniform illumination and PSCs. The 36 solar cells that made each solar module were connected together using MATLAB software in a variety of connection configurations, including Simple Series (S), S-P, T-C-T, B-L, and H-C. In a solar module, bypass diodes were also connected to prevent hot-spot circumstances. On the basis of distinct partial shading losses, the module configurations have been compared. The results demonstrated that the SP and HC module connectivity configuration in a PV module is more sensitive to power losses than other module interconnection configurations under non-uniform irradiation situations as well as various shading conditions.
Ishak et al. (2019) examined how various PV arrays performed under various shading scenarios. A 6x6 PV array was used to test four distinct PV array configuration techniques, including S, S-P, T-C-T, and BL array topologies. The modeling was developed using Matlab/Simulink. In terms of their highest output power, the PV array's performances and output characteristics were compared and assessed for four different configuration schemes. According to these results, when compared to other configurations, the T-C-T arrangement offered the highest maximum output power. Thus, the PV array's efficiency is significantly influenced by its configuration.
Patel et al. (2020) showed that PV array's configuration lessened the impact of partial shadowing situations on PV array configuration. A module of size 3X3 made of S, parallel (P), S-P, B-L, T-C-T, and H-C was created to evaluate the impact of solar PV modules on partial shade. In terms of open-circuit voltage, short-circuit current, global maximum power (GMPP), local maximum power (LMPP), V-I characteristics, etc., the results suggested that solar PV module configuration have been compared. Additionally, the suggested solar PV array arrangement may be validated using calculations for mismatching power losses, fill factor efficiency, and power productivity. It was found that the mismatching power loss grows with the number of series connections. According to observations and analysis, the mismatching power loss is greatly reduced when a bypass diode is included.

2. MATERIALS AND METHOD

2.1 Models of solar PV module

The practical equivalent circuit of the PV module simulated in the MATLAB/Simulink model is shown in Figure 1(a). Figure 1(b) shows the MATLAB/Simulink subsystem model of the PV module simulated under Standard Test Conditions (STC) of 1000 W/m^2 and 25°C. The simulated PV module and its parameters such as output power, voltage, current, and characteristic curves such as I–V and P–V are shown in Figure 1(c).

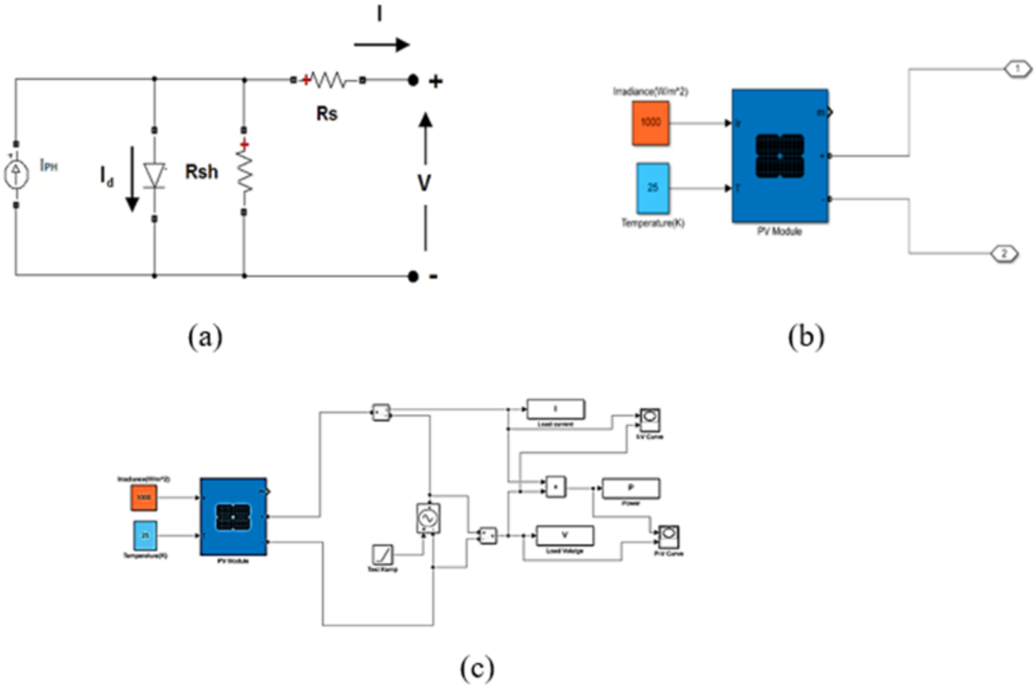


Fig. 1: PV module (a) Equivalent circuit (b) Subsystem model (c) Simulation model

2.2. Method of Performance Comparison

The performance of different array configurations is compared in terms of voltage at maximum power (V_m), current at maximum power (I_m), maximum power (P_m), mismatch loss (M_L), and fill factor.

• ***Maximum Output Power (P_m):*** This is the maximum power that can be delivered by the module to the load. Maximum power will be determined individually for the uniform irradiance and under the PSCs for each PV array configuration. P_m can be calculated according to equation (1)

$$P_m = V_{MPP} \times I_{MPP} \quad (1)$$

• ***Mismatching power loss, ΔP_L (%):*** Mismatching power loss can be calculated according to equation (2).

$$\Delta P_L(\%) = \frac{P_{MP} - P_{PSC}}{P_{MP}} \times 100 \quad (2)$$

where P_{MP} = Maximum power generated under uniform illumination condition
P_{PSC} = Maximum power generated under PSC

• ***Fill Factor (FF):*** It is a dimensionless quantity. Fill factor describes the quality of the solar cell by dividing the MPP by the product of open circuit voltage and short circuit current or in simple words, as implied by the name, FF is the ratio of the regions covered by the product of I_{MPP}-V_{MPP} and I_{SC}-V_{OC} rectangles, as seen in Figure 3.6. It indicates the squareness of the I-V curve. A cell with a square I-V curve is a better cell. The higher the FF, the better the cell. It deteriorates strongly with the inclusion of parasitic resistive components like the series resistance and shunt resistance.

$$FF = \frac{M_{PP}}{V_{OC} \times I_{SC}} \quad (3)$$

where M_{PP} = Maximum power point

$M_{PP} = V_{MPP} \times I_{MPP}$ (4)

- ***Performance ratio of PV array configurations:*** The performance ratio of PV array configurations is defined as the normalized value of power at GMPP under PSCs to the ideal conditions.

$$P_R\,(\%) = \frac{\text{GMPPatPSCs}}{\text{MPPatSTC}} \times 100 \quad (5)$$

2.3. Description of various PSCs on PV array configurations

Partial shading conditions (PSCs) significantly reduce the efficiency of PV systems by causing a loss of power in the PV array. Understanding the behavior of solar PV arrays under partial shading is crucial for optimizing their performance. Analysis is done to determine the performance of the mentioned PV array configurations of a 5x5 array involving five different shading conditions. In a PV array, based on the number of shaded modules per string (column) and the number of shaded rows, shading conditions are classified into five types; short and narrow; short and wide; long and narrow; long and wide; diagonal shading conditions. The description of each shading condition on 5 × 5 PV array configurations is shown in figure 2. (a-e).

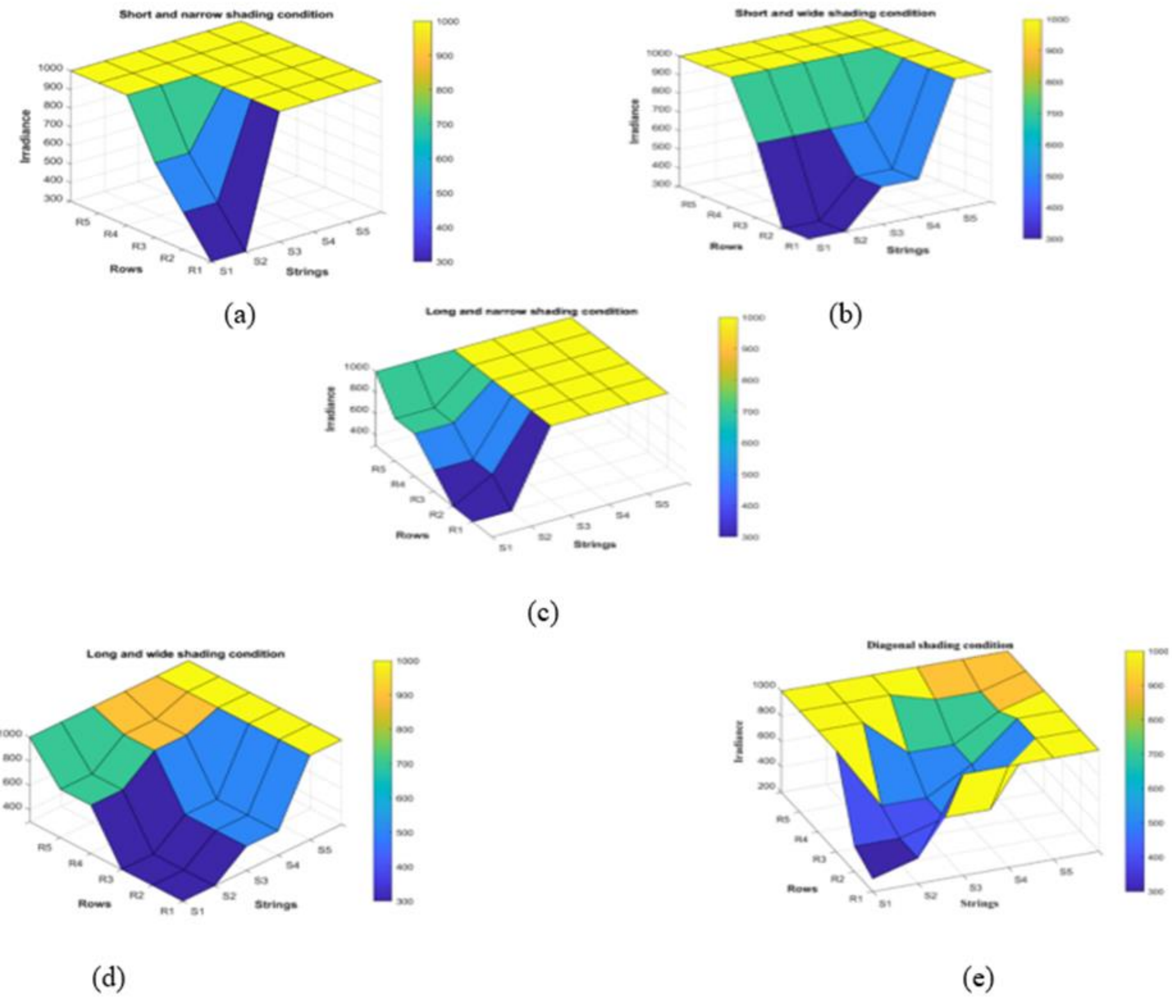


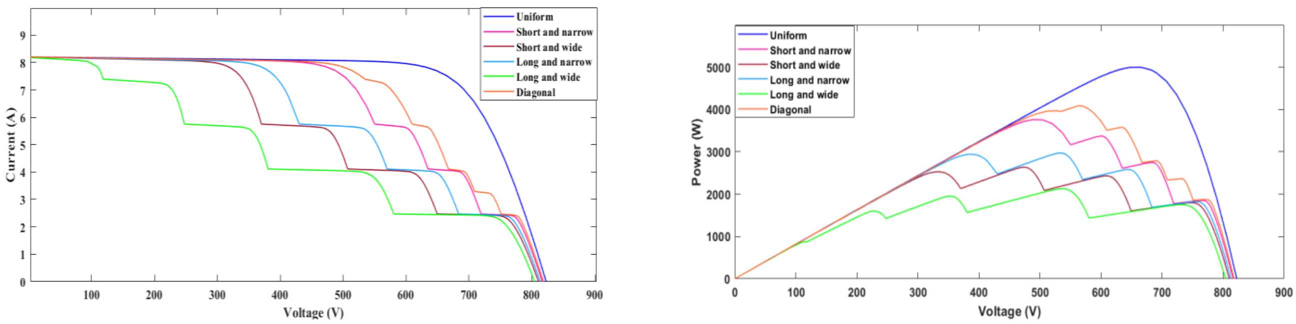
Fig. 2: PSCs (a) Short and narrow (b) Short and wide (c) Long and narrow (d) Long and wide (e) Diagonal

2.4 Modelling and simulation of PV array configurations

This section describes the modeling and simulation of different 5X5 PV array configurations. The performance of the examined configurations such as S, S-P, B-L, H-C, and T-C-T, under various PSCs is simulated and compared using the Matlab/Simulink software. For modeling these configurations, 25 PV modules are used and each module has series-connected 54 cells. All the 25 modules are arranged in five rows and five columns as 5×5 matrix structure. All the above-mentioned configurations are operated under various shading patterns as mentioned in Figure 2 and at constant temperature of 25◦C.

2.4.1 Series (S)PV array configurations

Series arrangement creates a continuous chain by connecting all the 25 PV modules in series. The PV array voltage is equal to the sum of the voltages of the individual PV modules and the array current is the same as the module current. However, series configurations face challenges like shading and mismatch losses, leading to reverse bias conditions that can cause hot spots and damage modules. To mitigate this, bypass diodes are used to prevent hot spot effects and ensure safe operation, resulting in multiple MPP on P-V characteristics. The lowest level of irradiance under PSCs limits the series PV array current.



(a) (b)

Fig 3: Output characteristics of Series PV array configuration under STC and PSCs (a) I-V curves (b) P-V curves

The Series PV array configuration achieves maximum power of 4997.93 watts at uniform irradiance but drops to 4085.46 watts under partial shade with diagonal shading. Figure 3. (a and b) indicates that specific shading patterns result in different maximum power outputs as Short and narrow: 3759.23 watts, Long and narrow: 2973.19 watts, Short and wide: 2635.95 watts, and Long and wide: 2127.83 watts.

2.4.2 Series-parallel (S-P) PV array configurations

To generate a desired output voltage, the PV modules are first connected in series to form strings and then these strings are then connected in parallel to produce the desired output current. The PV array voltage is equal to the total of each of the five PV module's voltage in a string, and the array current is the sum of each five string's currents. The output of the entire array won't be impacted significantly if one series circuit is shaded, unlike in a pure series configuration. As a result, the array gains additional redundancy and reliability. To safeguard each PV string against extreme PSCs or short circuit circumstances, blocking diodes are additionally connected in series. These diodes prevent the backflow of string current into another string.

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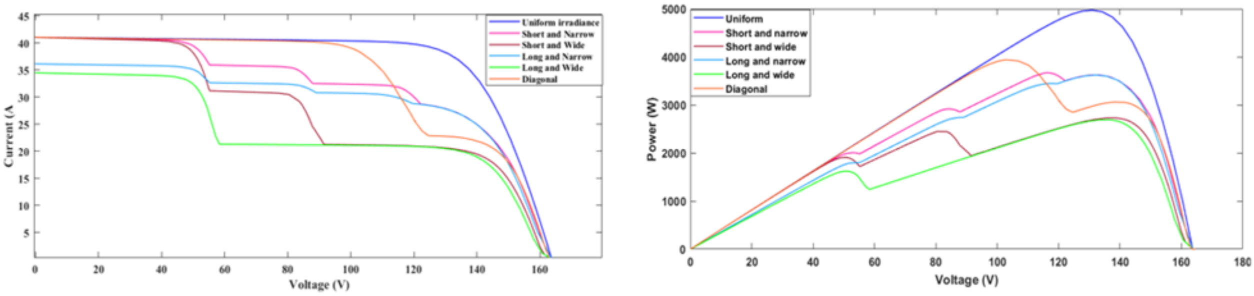
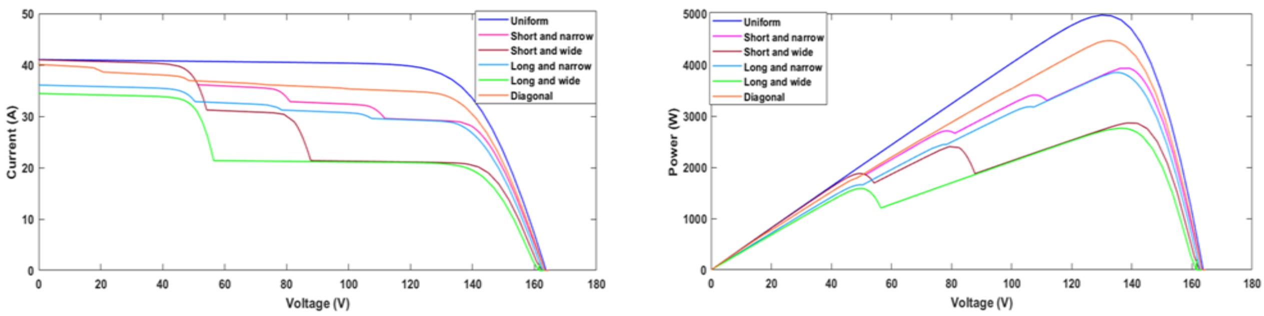


Fig 4: Output characteristics of S-P PV array configuration under STC and PSCs (a) I-V curves (b) P-V curves

The S-P PV array configuration achieves maximum power 4975 Watts at uniform irradiance but drops to 3939.78 watts under partial shade with diagonal shading. Figure 4. (a and b) indicates that specific shading patterns result in different maximum power outputs as Short and narrow: 3670 watts, Long and narrow: 3623.63 watts, Short and wide: 2730.89 watts, and Long and wide: 2693.118 watts.

2.4.3 Total-Cross-tied (T-C-T) PV array configurations

T-C-T configurations are frequently employed in commercial and large-scale PV projects, where shading, system dependability, and energy production optimization are crucial considerations. The S-P configuration is the source of the TCT configuration. The solar modules are arranged in rows and the rows are "cross-tied" to other rows rather than being directly connected to the inverter. This indicates that some of the rows are linked to one another in series, forming a grid-like design. After that, the cross-tied rows are linked in parallel to the inverter. The effects of shading or underperforming panels are lessened with the use of this parallel connection. It won't affect the entire array as it might in a conventional series setup when one row is darkened or has poor performance because the rows are cross-tied, only the impacted rows will experience reduced output if a portion of the array is shaded, leaving the remaining rows undisturbed.



(a) (b)

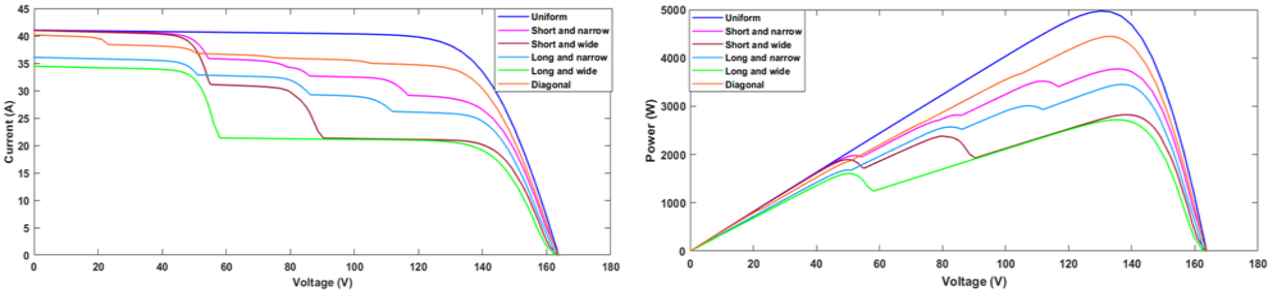
Fig. 5: Output characteristics of T-C-T PV array configuration under STC and PSCs (a) I-V curves (b) P-V curves

The T-C-T PV array configuration achieves maximum power 4975 watts at uniform irradiance but drops to 4470.85 watts under partial shade with diagonal shading. Figure 5. (a and b) indicates that specific shading patterns result in different maximum power outputs as Short and narrow: 3933.06 watts, Long and narrow: 3850.38 watts, Short and wide: 2866.28 watts, and Long and wide: 2763.53 watts.

2.4.4 Bridge-linked (B-L) PV array configurations

During PSCs, the S and S-P arrangement is the most affected because more modules are coupled in series. In a PV system, a bridge link is often the connection between several PV modules or strings to enhance the system's electrical properties.

All of the modules are connected in a bridge rectifier structure, which is commonly known as a B-L PV array structure. Initially the PV modules are split into pairs and each pair is connected in series when they are placed in a B-L configuration. Then multiple pairs of modules, are connected in parallel. Ties are present between the bridges. Hence the voltage and current values are obtained by appropriately adding voltages in series and currents in parallel.



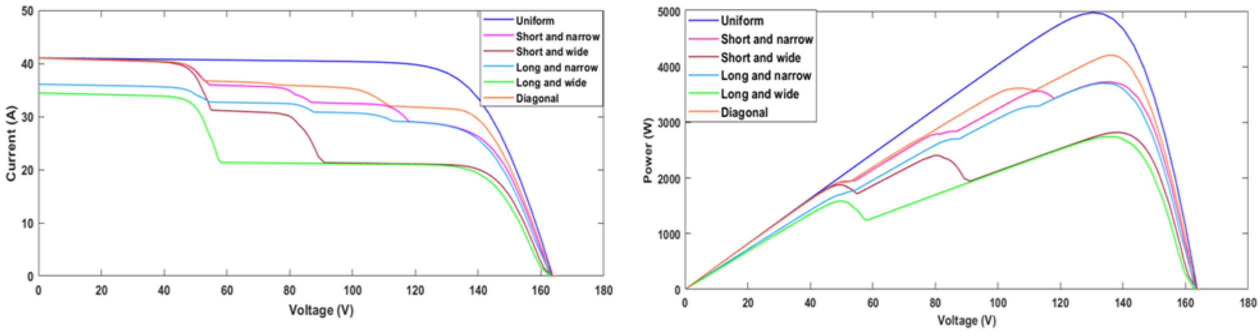
(a) (b)

Fig 6: Output characteristics of B-L PV array configuration under STC and PSCs (a) I-V curves (b) P-V curves

The B-L PV array configuration achieves maximum power 4975 Watts at uniform irradiance but drops to 4447.18 Watts under partial shade with diagonal shading. Figure 6. (a and b) indicates that specific shading patterns result in different maximum power outputs as Short and narrow: 3771.29 watts, Long and narrow: 3451.73 watts, Short and wide: 2824.57 watts, and Long and wide: 2719.25 watts.

2.4.5 Honey-Comb (H-C) PV array configurations

A new configuration called HC configuration has been created by making changes to the BL configuration. By simulating an HC PV array arrangement, the drawbacks of SP and BL topologies can be overcome. Basically, the design was influenced by the houses of honey bees. In contrast to S, S-P, and B-L PV array configurations, the H-C PV array architecture has a greater number of electrical connections between the PV modules and fewer series connections. As a result, H-C PV array configurations experience lower mismatching power losses than S, S-P, and B-L PV array configurations. Such a configuration cannot be clearly analyzed and requires additional computation. The H-C PV array configuration achieves maximum power 4975 watts at uniform irradiance but drops to 4208.48 watts under partial shade with diagonal shading. Figure 7. (a and b) indicates that specific shading patterns result in different maximum power outputs as Short and narrow: 3726.51 watts, Long and narrow: 3706.45 watts, Short and wide: 2820.07 watts, and Long and wide: 2743.40 watts.



(a) **(b)**

Fig 7: Output characteristics of H-C PV array configuration under STC and PSCs (a) I-V curves (b) P-V curves

3. RESULT AND DISCUSSION

This section includes a discussion of the results obtained from the simulation. The power of the PV array varies in accordance with the shading pattern. Changing shading conditions result in

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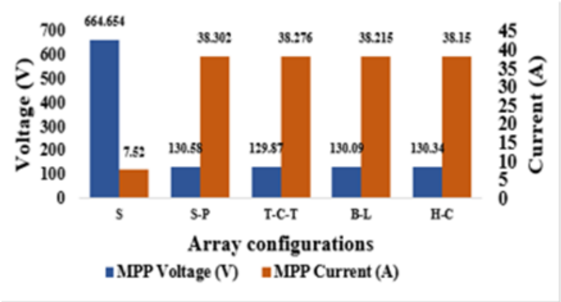
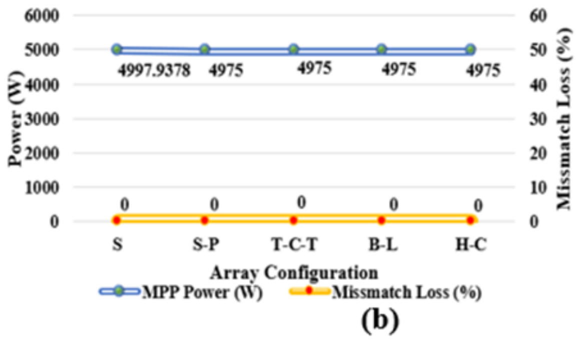
varied I-V and P-V characteristics for the same PV array configuration of solar modules. The maximum powers for each and every array configuration under each shading pattern are compared using the I-V and P-V characteristics. The best PV array configuration is determined for each shading pattern based on the computation of shading loss (P_S), mismatch power losses (ΔP_L in %), performance ratio (PR in %), and fill factor (FF).

3.1 Under uniform irradiance condition

In a 5X5 PV array design, all the PV modules are exposed to an irradiation of 1000 W/m^2 under the situations of uniform irradiance. According to the simulated output characteristics of the S, S-P, T-C-T, B-L, and H-C PV array configurations generate the almost same voltage and current at a maximum power of 4975 W under the STC conditions, while the maximum power generated by the series PV array configuration is 4997.93 watts and a single MPP on output characteristics, which is known as a global MPP (GMPP).





(a) (b)

Fig 8: Under STC(a)maximum power and mismatching losses(b)MPP voltages and currents

Figure 8. (a) displays the generated MPP voltages and MPP currents for the S, S-P, T-C-T, B-L, and H-C PV array configurations. So, it is clear from the observation that for the high voltage and low current application when all the configurations are subjected to the uniform irradiance level, series PV array configuration is best but in the case of the low voltage and high current application any of the other configurations in S-P, T-C-T, B-L, and H-C will be the suitable PV array configuration. For all the configurations, the mismatch loss is almost zero and fill factor is 0.75. In Figure 8. (b), mismatching losses and the maximum power produced by the S, S-P, T-C-T, B-L, and H-C PV array topologies are depicted.

3.2 Short and narrow shading condition

Under short and narrow shading conditions, the T-C-T array arrangement, generates three MPPs based on output characteristics and achieves the highest maximum power of 3933.06 watts under this shading scenario. Figure 9.(a) displays the highest power generated and mismatching losses. Mismatching losses driven by S, S-P, T-C-T, B-L, and H-C array topologies are 24.78%, 26.23%, 20.94%, 24.19%, and 25.09%, respectively. Figure 9.(b) displays the highest produced voltages and currents for the S, S-P, T-C-T, B-L, and H-C configurations at MPP. S, S-P, T-C-T, B-L, and H-C array configurations have fill factors of 0.56, 0.54, 0.58, 0.55, and 0.55, respectively as shown in Figure 9.(c).

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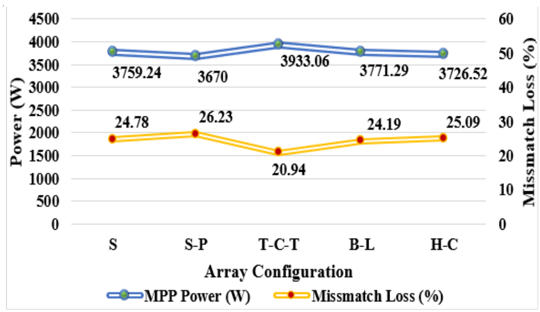
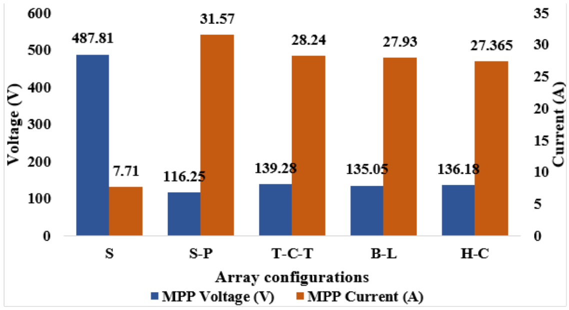


(a)



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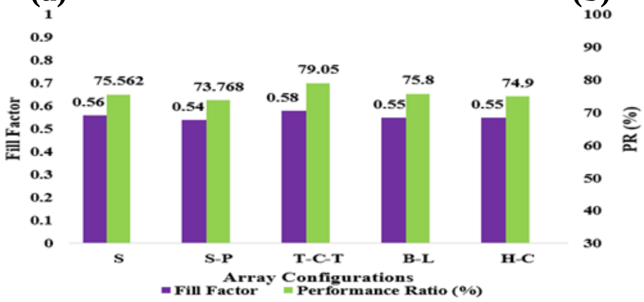


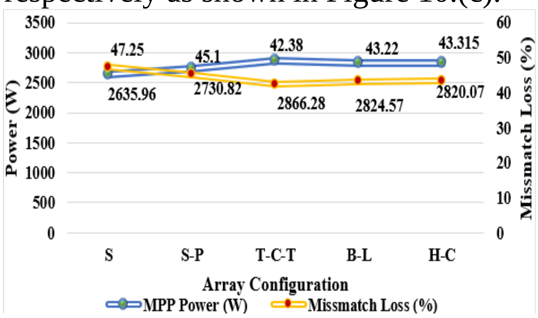
(c)

Fig 9: Under short and narrow PSCs (a)Maximum power and mismatching losses(b)MPP voltages and currents (c) Fill factor and performance ratio

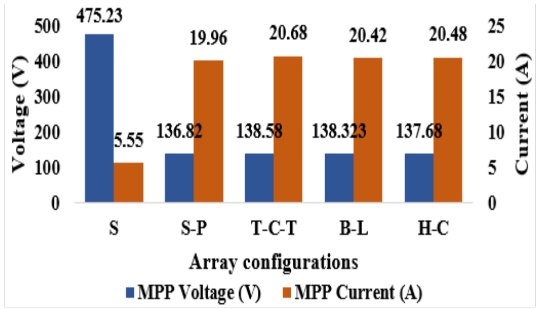
As a result of the analysis, it is observed that the T-C-T array layout is the best configuration for generating maximum power while minimizing mismatching losses under short and narrow shadowing conditions. Despite the fact that the T-C-T array design also possesses the greatest FF and PR (79.05) if any, it is obvious that this configuration is the most effective array for this shading scenario. While under this shading environment, the B-L and H-C exhibit the almost same performance.

3.3 Short and wide shading condition

Under short and wide shading conditions, The T-C-T array arrangement, which generates a maximum power of 2866.28 watt under this shading scenario. Figure 10.(a) displays the highest power generated and mismatching losses caused by the S, S-P, T-C-T, B-L, and H-C array designs. Mismatching losses driven by the S, S-P, T-C-T, B-L, and H-C array topologies are 47.25%, 45.1%, 42.38%, 43.22%, and 43.315%, respectively. Figure10.(b) displays the produced voltages and currents at GMPP for the S, S-P, T-C-T, B-L, and H-C designs. These designs have fill factors of 0.39, 0.4, 0.423, 0.417, and 0.416, respectively as shown in Figure 10.(c).



(a)



(b)

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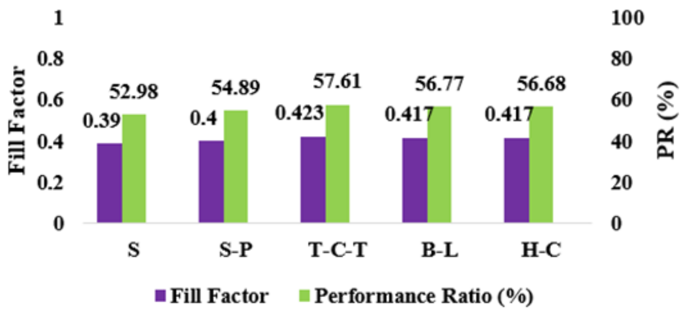


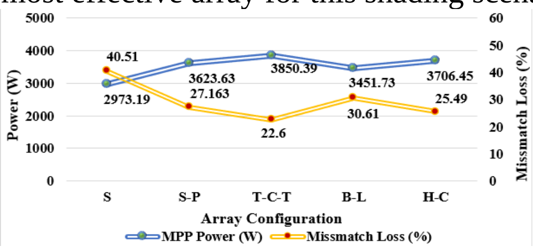
(c)

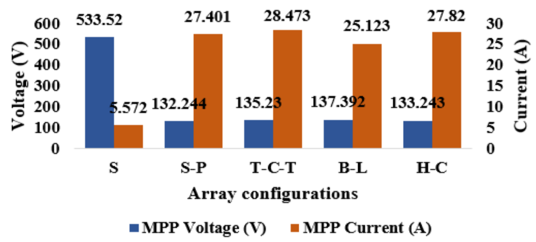
Fig 10: Under short and wide PSCs(a) Maximum power and mismatching losses (b)MPP voltages and currents (c) Fill Factor and performance ratio

As a result of the analysis, it is observed that the T-C-T array layout is the best configuration for generating maximum power while minimizing mismatching losses under short and wide shadowing conditions. Despite the fact that the T-C-T array design also has the greatest FF (0.423) and PR (57.61) if any, it is obvious that this configuration is the most effective array for this shading scenario. While under this shading environment, the B-L and H-C exhibit the almost same performance as the T-C-T array configuration. Therefore, in this shading scenario, B-L and H-C topologies can be offered in place of the T-C-T array design.

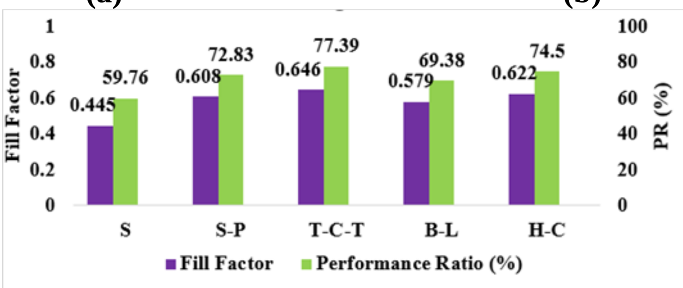
3.4 Long and narrow shading condition

Under long and narrow shading conditions, The T-C-T array arrangement, generates a maximum power of 3850.39 watts under this shading scenario. Fig. 11(a) displays the highest power generated and mismatching losses caused by the S, S-P, T-C-T, B-L, and H-C array designs. Mismatching losses driven by the S, S-P, T-C-T, B-L, and H-C array topologies are 40.51%, 27.163%, 22.6%, 30.61%, and 25.49%, respectively. Figure 11(b) displays the voltages and currents produced for the S, S-P, T-C-T, B-L, and H-C designs at GMPP. These designs have fill factors of 0.45, 0.61, 0.65, 0.58, and 0.62, respectively, shown in Figure 11(c). As a result of the analysis, it is observed that the T-C-T array layout is the best configuration for generating maximum power while minimizing mismatching losses under long and narrow shadowing conditions. Despite the fact that the T-C-T array design also has the greatest FF (0.65) and PR (77.39) if any, it is obvious that this configuration is the most effective array for this shading scenario.





(a) **(b)**



(c)

Fig 11: Under long and narrow PSCs(a) Maximum power and mismatching losses (b)MPP voltages and currents(c) Fill Factor and Performance Ratio

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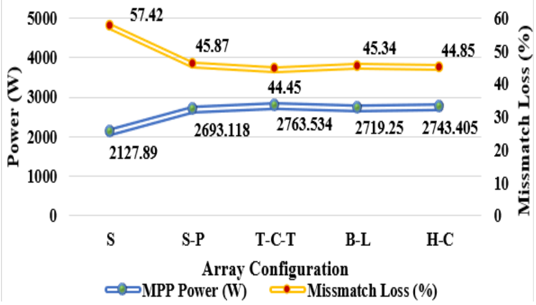
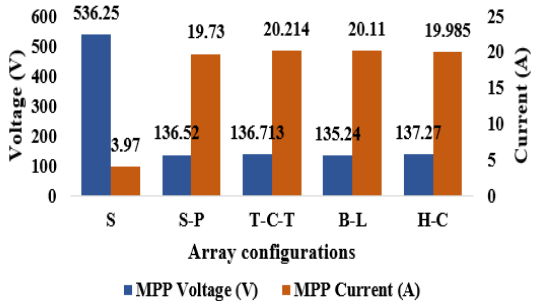
3.5 Long and wide shading condition

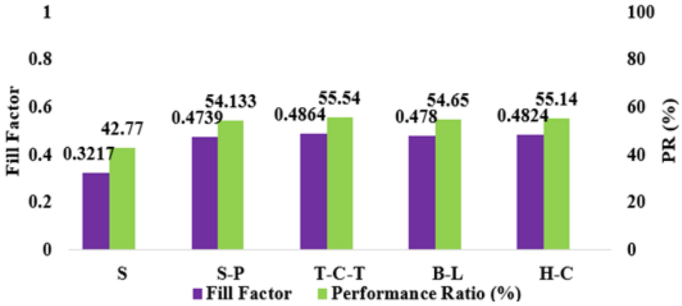
Under long and wide shading conditions, the T-C-T array arrangement, which generates a maximum power of 2763.54 watts under this shading scenario. Figure 12.(a) displays the highest power generated and mismatching losses caused by the S, S-P, T-C-T, B-L, and H-C array designs.



(a)



(b)



(c)

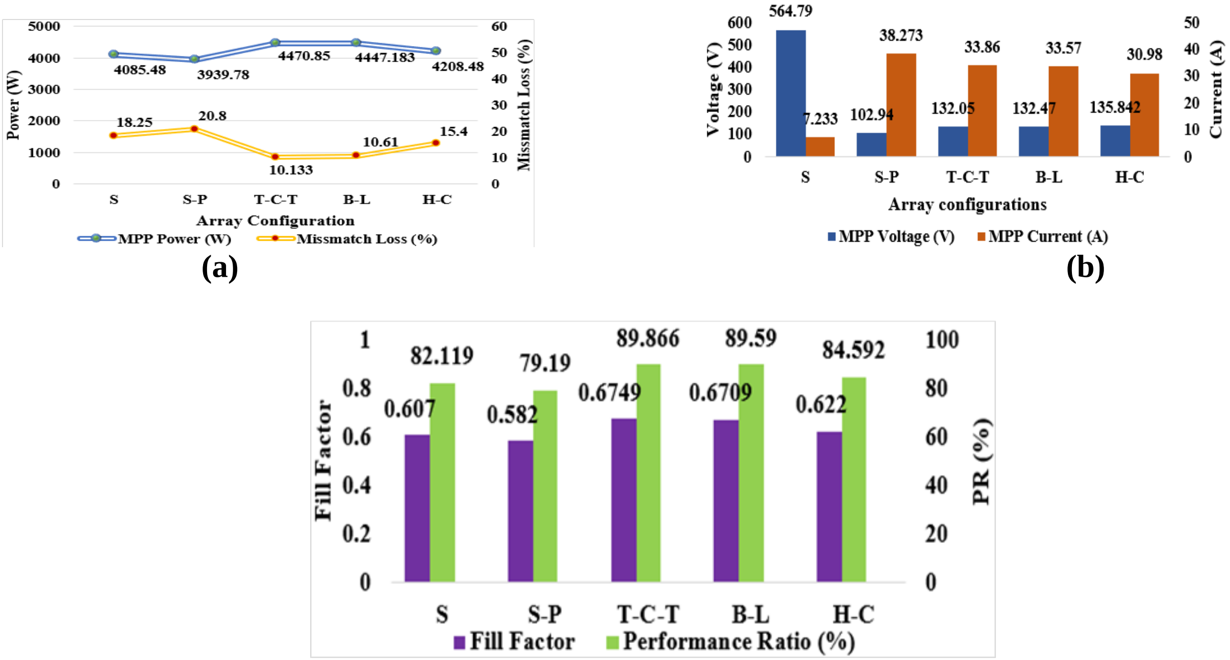
Fig 12: Under long and wide PSC(a)Maximum power and mismatching losses (b)MPP voltages and currents (c) Fill factor and performance ratio

Mismatching losses driven by the S, S-P, T-C-T, B-L, and H-C array topologies are 57.42%, 45.87%, 44.45%, 45.34%, and 44.85%, respectively. Figure 12(b) displays the highest produced voltages and currents for the S, S-P, T-C-T, B-L, and H-C designs at GMPP. These designs have fill factors of 0.32, 0.48, 0.49, 0.478, and 0.483, respectively which are shown in Figure 12(c).

As a result of the analysis, it is observed that the T-C-T array layout is the best configuration for generating maximum power while minimizing mismatching losses under short and narrow shadowing conditions. Despite the fact that the T-C-T array design also has the greatest FF (0.49) and PR (55.54) of any, it is obvious that this configuration is the most effective array for this shading scenario. While under this shading environment, the B-L and H-C exhibit the almost same performance as the T-C-T array configuration. Therefore, in this shading scenario, B-L and H-C topologies can be offered in place of the T-C-T array design.

3.6 Diagonal shading condition

Under diagonal shading conditions, The T-C-T and B-L array arrangements, generate almost the same maximum power of 4470.84 watts and 4447.183 watts respectively under this shading scenario. Figure 13(a) displays the highest power generated and mismatching losses caused by the S, S-P, T-C-T, B-L, and H-C array designs. Mismatching losses driven by the S, S-P, T-C-T, B-L, and H-C array topologies are 18.25%, 20.8%, 10.133%, 10.61%, and 15.4%, respectively. Figure 13(b) displays the maximum generated voltages and currents for the S, S-P, T-C-T, B-L, and H-C designs at MPP. These designs have fill factors of 0.61, 0.58, 0.68, 0.67, and 0.62 respectively shown in Figure 13(c).



(a) (b)

(c)

Fig 13: Under diagonal PSC(a)Maximum power and mismatching losses (b)MPP voltages and currents (c) Fill factor and performance ratio.

As a result of the analysis, it is observed that the T-C-T and B-L array layouts are the best configurations for generating maximum power while minimizing mismatching losses under diagonal shadowing conditions. Despite the fact that the T-C-T array design also has the greatest FF (0.68) and PR (89.86), it is obvious that this configuration is the most effective array for this shading scenario. While under this shading environment, the B-L exhibits almost same performance as the T-C-T array configuration. Therefore, in this shading scenario, B-L topologies can be offered in place of the T-C-T array design.

4. Conclusion

Integrating PV systems into the grid, demands efficient power extraction, especially under partial shading conditions (PSCs) caused by various factors such as dusting, spatial location, and land orientation. PSCs significantly hampers PV system performance. PV array configurations based on interconnections used between PV modules are a highly effective approach to minimize power losses due to PSCs.

From the simulation results, it is observed that during uniform irradiance or STC, there is no difference in output characteristics of S-P, T-C-T, B-L, and H-C PV array configurations and it produces almost equal amount of maximum power but series PV array configuration generates maximum power over other PV array configuration. So, under STC, the series PV array configuration is an optimal PV array configuration amongst all the mentioned PV array configurations. Under the short and narrow shading condition, the T-C-T configuration gives the optimum performance in terms of mismatch losses, fill factor, performance ratio, and maximum power over other PV array configurations. Series PV array configuration performs better in comparison to S-P and H-C. The S-P configuration gives poorest performance under short and narrow shading condition. While series configuration performs poorest under short and wide, long and narrow, and long and wide PSCs among all other PV array configurations and T-C-T configuration gives optimum performance in terms of mismatch losses, fill factor, performance ratio, and maximum power over other PV array configuration under these PSCs. The B-L and H-C exhibits the nearly same performance as the T-C-T array configuration under the short and wide, and long and wide PSCs. Therefore, in this shading scenario, B-L and H-C topologies can be offered in place of the T-C-T array design. In the case of diagonal

PSCs, the performance of S-P is poorest among all mentioned PV array configurations. T-C-T and B-L configurations shows optimum performance in terms of mismatch losses, fill factor, performance ratio, and maximum power over other PV array configurations. Therefore, in this shading scenario, T-C-T and B-L topologies are best and can be offered. Hence, the results of simulations on various array configurations demonstrate that, due to the greater number of parallel routes in the T-C-T configuration, it is least susceptible to shading losses under partial shading conditions, whereas the series configuration due to the more series connection exhibits the highest shading losses. Moreover, the performance of BL and HC are approximately close to each other. In some PSCs, the BL configuration performs well, while in others, the HC configuration outperforms the BL configuration. However, in all shading conditions, the T-C-T configuration performs better than all other configurations.

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