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Comparison of the Performance of Different PV System Configurations Under Partial Shading

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Abstract

This paper aims to analyze the performance of various photovoltaic (*PV*) array configurations under different partial shading conditions. With the growth of solar energy adoption, *PV* systems are increasingly installed in environments where shading from buildings, trees, or obstacles is common. Partial shading disrupts light distribution on PV modules, leading to power losses, particularly in series configurations where shading of a single module can affect the entire string. To address this, configurations like Serie (S), Series-Parallel (SP), Honey-Comb (HC), Total Cross-Tied (TCT), and Bridged-Link (BL) have been developed to enhance shading resilience. Using MATLAB/Simulink simulations, these configurations were tested under four shading levels—0%, 20%, 40%, and 60%—to observe their power-voltage (*P-V*) and current-voltage (*I-V*) characteristics. The TCT configuration demonstrated the highest resilience to shading, maintaining a higher fill factor and power output compared to the other configurations. Results indicate that TCT configuration offers the highest resilience, producing 2672 W and 2524 W at 40% and 60% shading, respectively, significantly outperforming series configurations, which show substantial power reductions. The BL and HC configurations also demonstrate superior performance, with fill factor values that confirm the robustness of Total-Cross-Tied (TCT) against shading effects. OverallThe Total-Cross-Tied (TCT) configuration proved the most effective in reducing energy losses in shaded conditions. These findings suggest that the TCT configuration is best suited for environments with high shading risk, while the Series configuration performs well in unshaded conditions. This research underscores the importance of PV configuration choice for sustainable energy performance in real-world settings where shading is a concern.

Keywords: *Photovoltaic Configurations, Partial Shading, MATLAB/Simulink, Power Output, Fill factor*

1. Introduction

As the adoption of solar energy continues to grow, photovoltaic systems are increasingly deployed in diverse environments, including those susceptible to shading from buildings, trees, or other obstacles. Partial shading can significantly reduce the energy yield of PV arrays, as it disrupts the uniform distribution of light across the modules, leading to mismatched outputs within the system [1]. This shading effect is especially problematic for series configurations, where even a small portion of shading on a single module can lead to substantial power losses [2]. Consequently, improving the resilience of *PV* configurations to shading has become essential for enhancing their efficiency and reliability in practical applications. Various array configurations, such as Series (S), Series-Parallel (SP), Bridged-Link (BL), Total Cross-Tied (TCT) and Honey-Comb (HC), have been developed in the literature. These configurations are designed to handle shading differently, enabling some systems to sustain higher power outputs and maintain efficiency even when shaded. [3]. This study measures the performance of these configurations under varying shading scenarios using MATLAB/Simulink simulations. By examining characteristics of PV module under controlled shading scenarios, the study aims to determine which configurations best retain performance. The results demonstrate that the TCT configuration shows the greatest resilience to shading. the TCT may be the optimal choice for shading-prone environments [4].

2. PV array configuration

The photovoltaic system configurations mentioned in the literature to mitigate the shading effect are shown in Figure 1.

2.1. Series Configuration

In the series configuration, the photovoltaic panels are connected to each other in a single string. This arrangement increases the total voltage, as the voltage of each module adds to that of the others [5]. The maximum voltage (V_{max}), current (I_{max}), and power (P_{max}) of each panel are its output parameters while the

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photovoltaic system is working correctly. The main advantage of this configuration is its simplicity and efficiency under optimal sunlight conditions, allowing for maximum power output. nevertheless, an important weakness is that the performance of the whole series will be limited, leading to significant power losses, if one panel in the string is shaded. The model used in this research is a 4x4 panels [6].

2.2. Serie-Parallel Configuration

Initially, the PV modules get connected in series to form strings. Several strings then connect in parallel. This configuration allows both voltage (via series connection) and current (via parallel connection) to be increased. The advantage of this configuration is that in the event of partial shading, only the affected string experiences reduced performance, while the other strings continue to operate normally. However, shading on an entire string can lead to significant power losses [7].

2.3. Total Cross-Tied Configuration

The TCT configuration is an improvement over the Serie-Parallel configuration, where cross ties are added between the modules in each row. This helps balance the voltage across rows of modules and distribute the current more evenly among columns. In the event of partial shading, this configuration allows losses to be limited by distributing the current through unaffected modules. As a result, the system's performance is less sensitive to shading compared to series or series-parallel configurations [7].

2.4. Bridged-Link Configuration

The bridged-link configuration is another variant that combines features of both series and parallel connections, while introducing "bridges" between some modules. These bridges are formed by connecting two modules in series, and then linking those series connections in parallel. The bridges are further connected by cross ties to create a more robust structure against partial shading. The main advantage of this configuration is that it reduces power losses under shading conditions, as currents can flow through multiple alternative paths [8].

2.5. Honey-Comb Configuration

The HC configuration is an adaptation of the bridged-link array, featuring adjustable bridge sizes. The panels are connected in series within small bridges, which are connected by cross ties, just like in the BL array. The honey-comb structure allows for more efficient current distribution across the modules, minimizing power losses [9].

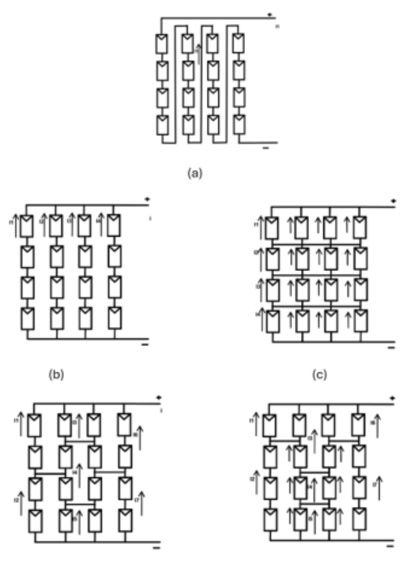

Figure 1: PV configurations: a) Serie, b) Serie-Parallel, c) Total-Cross-Tied, d) Bridged-Link, e) Honey-Com

3. Analysis of partial shading conditions

3.1. MATLAB/Simulink Simulation of PV Configurations

In this section, the different configurations previously mentioned are simulated using MATLAB/Simulink .Table 1 presents the characteristics of the panel.The simulation models for the five topologies are shown, with the Total-Cross-Tied (TCT) topology illustrated in Figure 2. The main inputs for the simulations are temperature and irradiation. Since we are only focusing on the effects of partial shading, At 25°C, the temperature is maintained consistently.

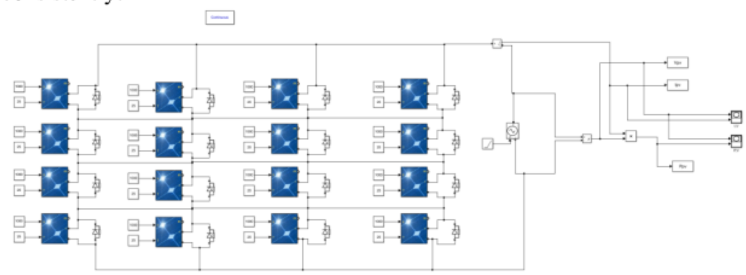

Figure 2. Simulink model for TCT configuration.

Table 1. characteristics of PV panel [10]

Parameters	Values
P_{max}	250 W
V_{mpp}	30.96 V
I_{mpp}	8.07 A
V_{oc}	37.92 V
I_{sc}	8.62 A
a	0.99132
R_{sh}	82.1161 Ω
V_{oc}(%/deg.C)	-0.33969
I_{sc}(%/deg.C)	0.063701

3.2. Shading patterns

We have simulated various partial shading scenarios to evaluate their impact on the performance of different photovoltaic configurations. Specifically, we applied targeted partial shading to four modules located on the left-hand side and the bottom of each configuration. These areas were chosen due to their susceptibility to common sources of shading, such as buildings, trees, or other obstacles in real-world environments [11]. As shown in Figure 3, shading was applied at four levels: 0% (no shading), 20% , 40%, and 60%, to replicate a range of realistic partial shading conditions that could impact energy production. This variation allowed us to assess how each PV system configuration responds to reduced irradiance, which can significantly impact the system's overall efficiency.

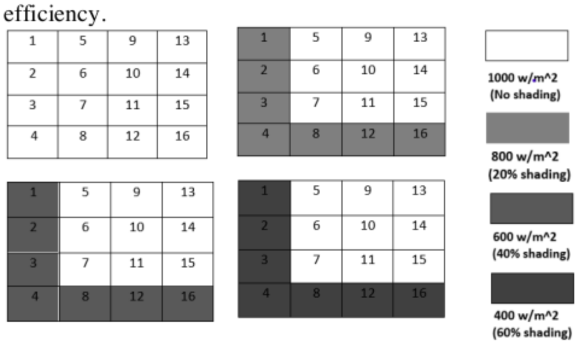

Figure 3. Pattern shading scenario.

4. Results and Discussion

We have generated the *P-V* (power-voltage) and *I-V* (current-voltage) curves for each configuration, simulating various levels of partial shading: 0%, 20%, 40%, and 60%. These curves allow us to visualize the impact of shading on system performance and observe changes in the maximum power point (MPP), as well as fluctuations in current and voltage. This analysis will serve as the basis for evaluating which configuration is the most resilient to The negative effects of partial shading. Table 2 presents the simulation results for maximum output current voltage, and power under differents shading levels.

Table 2. Output power, current, and voltage under various shading levels.

Shading level	Configuration	P_{max} (W)	V_{max} (V)	I_{max} (A)
	S	3997	497.5	8.033
	SP	3997	124.4	32.13
No Shading	TCT	3997	124.4	32.13
	BL	3997	124.4	32.13
	HC	3997	124.4	32.13
	S	3398	509.6	6.68
	SP	3391	127.4	26.61
20% Shading	TCT	3441	127.4	27
	BL	3419	127.4	26.84
	HC	3402	127.4	26.7
	S	2617	521.8	5.015
	SP	2581	130.4	19.79
40% Shading	TCT	2672	133.5	20.02
	BL	2634	130.4	20.19
	HC	2604	130.4	19.97
	S	2193	279.1	7.857
	SP	2540	94.04	27.01
60% Shading	TCT	2524	91.01	27.73
	BL	2529	91.01	27.79
	HC	2533	94.04	26.93

According to Table 2, the TCT configuration demonstrates the higher power output under shading scenarios, producing 2672 W at 40% shading and 2524 W at 60% shading. In contrast, the series(S) configuration drops to 2617 W and 2193 W, respectively. The Serie-Parallel (SP), Bridged-Link (BL), and Honey-comb (HC) configurations yield slightly lower outputs, with SP at 2540 W, BL at 2529 W, and HC at 2533 W at 60% shading. The superiority of the Total-Cross-Tied can be attributed to its ability to bypass shaded panels effectively, allowing for better energy harvesting. On the other hand, the series configuration suffers from its dependence on all panels, leading to significant performance losses. This analysis confirms that Total-Cross-Tied is the most resilient configuration, when there is shading, the series structure is extremely vulnerable. Moreover, the effect of shading on photovoltaic field performance is also determined by comparing the fill factor results of shading situations.

4.1 Fill factor

This factor is crucial for identifying the effect of shading, as a noticeable decrease in the fill factor indicates an efficiency loss due to shaded areas. The fill factor can be determined using Equation. Table 3 shows the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}). Table 4 shows the filling factor values. [12]:

$$FF = \frac{P_{max}}{V_{oc} I_{sc}} \quad (1)$$

Table 3. The short circuit current and open circuit voltage of various configurations.

Shading level		S	SP	TCT	BL	HC
No Shading	V_{oc} (V)	606.72	151.7	151.6	151.7	151.7
	I_{sc} (I)	8.62	34.52	34.52	34.52	34.52
20%Shading	V_{oc} (V)	603	148.6	148.6	148.6	148.6
	I_{sc} (I)	8.62	32.79	32.79	32.79	32.79
40%Shading	V_{oc} (V)	600	150	150.1	148	147
	I_{sc} (I)	8.62	31.07	31.02	31.02	31.02
60%Shading	V_{oc} (V)	594.6	149.6	149.6	149.6	149.6
	Isc (I)	8.62	29.29	29.29	29.34	29.4

Table 4: Fill factor values

Configurations	No Shading	20%Shading	40%Shading	60%Shading
S	0.77	0.65	0.42	0.42
SP	0.76	0.69	0.55	0.57
TCT	0.76	0.71	0.58	0.58
BL	0.76	0.70	0.57	0.57
HC	0.76	0.70	0.57	0.57

Figure 4 provides a graph illustrating the impact of different shading levels on the performance of various photovoltaic configurations. Without shading, all configurations show a high fill factor, around 0.76 to 0.77, indicating optimal performance. However, with 20% shading, there is a slight decrease for all configurations, although TCT (0.71) and BL (0.70) maintain the highest performance, showing better shade tolerance compared to others.
At 40% and 60% shading, the impact becomes more significant, especially for configuration S, which drops to 0.42, while Total-cross-Tied (TCT) remains higher at 0.58, followed by Bridged-Link (BL) and Honey-Comb (HC) at 0.57. This increased resilience of TCT under partial shading makes it the most performant configuration in shaded environments, while S is better suited for non-shaded conditions to achieve optimal performance.

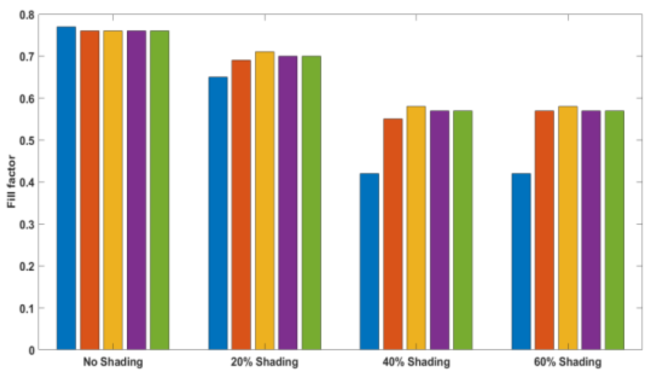

Figure 4. Fill factor for different configurations

5. Conclusion

This article analyzed partial shading on different configurations of *PV* systems using MATLAB/Simulink simulations. Configurations like Series-Parallel (SP), Serie (S), Total Cross-Tied (TCT), Honey-Comb (HC), and Bridged-Link (BL), were evaluated for their performance under shading scenarios. conditions. The results show that the Total-Cross-Tied (TCT) configuration offers the best resilience and superior energy production even in challenging conditions. In contrast, series systems experience significant performance losses. The efficiency of all other configurations was verified by the examination of *I-V* and *P-V* curves and fill factor values. These findings emphasize the importance of making a judicious choice of PV system configuration to optimize energy production in shading-prone environments.

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