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A comparative study of solar photovoltaic array configurations to optimize power harvesting in a real-world system under various partial shading conditions

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ABSTRACT

Partial shading (PS) significantly reduces power generation and efficiency in solar photovoltaic (PV) systems. This research presents a novel totalcross-tied (TCT) methodology designed to mitigate shading effects by optimizing array layout while preserving electrical connectivity. The TCT method is compared to three established configurations: series-parallel (S-P), bridge-linked (B-L) and honey-comb (H-C). MATLAB simulations on a (9×9) PV array under variousshading conditions demonstrate TCT's superior performance in achieving the global maximum power point (GMPP). Key findings indicate that TCT surpasses the other configurations, reaching a maximum power output of 16,650W at GMPP, with a mismatch power loss of 2,600W, a power loss of 13.32%, a fill factor (FF) of 38.27, and an execution ratio (ER) of 0.866.

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1. INTRODUCTION

The rising worldwide need for affordable, sustainable energy options has greatly boosted interest in solar photovoltaic (PV) systems. These systems offer a practical means of converting sunlight into electricity; however, their performance can be significantly affected by environmental elements like solar irradiation, temperature changes, dust accumulation, and especially partial shading conditions (PSCs) [1], [2]. PS remains one of the major unresolved challenges in solar PV systems, as it introduces multiple maximum power points (MPPs) in the system's current-voltage and power-voltage characteristics, leading to inefficient energy harvesting and complicating MPP tracking (MPPT) efforts [3].

Several notable contributors have proposed solutions to mitigate the effects of PSCs. Ebhota and Jen [4] explored renewable energy systems to overcome fossil fuel issues. The authors found that the solar PV can be pivotal in transitioning only to hybrid energy systems. Yadav *et al.* [5] developed a magic-square puzzle PV array configuration. In this the performance was improved by evenly distributing shading effects. Oufettoul *et al.* [6] compared PV module arrangements under shading. They found optimal layouts can reduced by shading impacts. Fu *et al.* [7] used Fresnel lenses for uniform illumination. They maintained consistent power output under sunlight concentration. Madhanmohan *et al.* [8] proposed a diagonally dispersed totalcross-tied (TCT) configuration. The output was improved under PS compared to traditional layouts. Kadhim *et al.* [9] reviewed PV array reconfiguration methods under PSC. The authors highlighted those physical reconfigurations and intelligent strategies significantly mitigate shading losses.

Roman *et al*. [10] developed a micro-inverter MPPT system with individual inverters for each PV module connected to a common AC bus, but the high cost of micro-inverters was a significant drawback. Dhople *et al*. [11] proposed a multiple-input boost converter for MPPT in series strings of solar cells with bypass diodes, suitable for distributed MPPT systems using micro-inverters. Koutroulis and Blaabjerg [12] introduced a new MPPT technique for tracking the GMPP of PV arrays under PS conditions (PSCs) using a D-flip/flop and analog/digital converter. Pandem and Mikkili [13] compared large S and S–P PV array configurations under PSCs, using MATLAB/Simulink for modeling and analysis, revealing that global peak power is affected by array configuration and shading patterns. Ajmal *et al*. [14] provided a brief comparison of PV array configurations under row and column shading, discussing challenges in reconfiguration methods for maximizing power in PV systems.

Ranjbaran *et al*. [15] studied floating PV (FPV) systems with various PV array designs. Bhatnagar *et al*. [16] evaluated multiple MPPT algorithms for optimizing power extraction by adjusting device input impedance to match the PV array's MPP.. These works consistently highlight that intelligent configuration and dynamic array management can significantly improve energy output. Despite these advances, several limitations persist, including the complexity of physical reconfigurations, the need for numerous switches and sensors, the cost implications of dynamic reconfiguration systems, and the challenge of handling dynamic, real-world shading scenarios in a scalable, efficient manner.

This research proposed a comprehensive evaluation of the effective TCT PV array design to address existing challenges. While previous studies have explored TCT configurations, this study specifically analyzes their performance through MATLAB/Simulink simulations under four shading patterns (Short-wide, short-narrow, long-narrow, and center shading) on an (8×8) system at the Mahatma Gandhi Post Graduate Institute of Dental Sciences (MGPGIDS) in Puducherry, India. Unlike earlier efforts, this research seeks to enhance performance without complex reconfiguration or additional hardware, emphasizing practical application in real PV systems.

The paper is organized as follows: section 2 discusses the modeling of PV cells and modules. Section 3 presents the mathematical analysis of different PV array configurations: series-parallel (S-P), bridge-linked (B-L), honey-comb (H-C), and the proposed TCT arrangement. Section 4 covers the performance metrics of solar PV systems. Section 5 reviews simulation results and analyzes the performance of each configuration under varying shading conditions. Finally, section 6 concludes the findings, highlighting the TCT configuration's superiority in enhancing PV system efficiency under PS.

2. MODELLING OF SOLAR PHOTO-VOLTAIC SYSTEMS

The performance evaluation of PV array is heavily reliant on the modelling of the PV cell, making it a crucial factor. There are various techniques for representing PV cells in research papers, including the single diode, dual diode, and triple diode models [17]. The PV cell behavior was modeled using a singlediode equivalent model because it is a well-validated, industry-standard approach that enables high-fidelity yet computationally efficient modeling, crucial for analyzing large arrays under multiple scenarios. This model effectively captures essential PV characteristics like diode ideality factor, series resistance, and reverse saturation current, which are critical under non-uniform irradiance conditions. The relation between the SPV cell's voltage and current is shown in the following equation [18],

$$I = I_L - I_0 \left[exp\left(\frac{V+IR_s}{\eta V_T}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \quad (1)$$

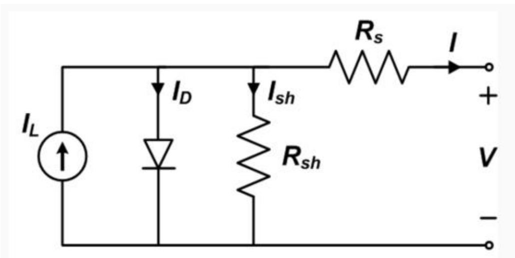


Figure 1. Equivalent cell modelling using single diode

3. DIFFERENT PV ARRAY CONFIGURATIONS

Four distinct PV array interconnection structures were developed in an (8×8) matrix (64 modules) as shown in Figure 2 and Figure 3. PV module interconnection styles, Figure 2(a) is S-P and Figure 2(b) is B-L. Meanwhile, Figure 3(a) shows H-C and Figure 3(b) shows the proposed TCT.

3.1. S-P configuration

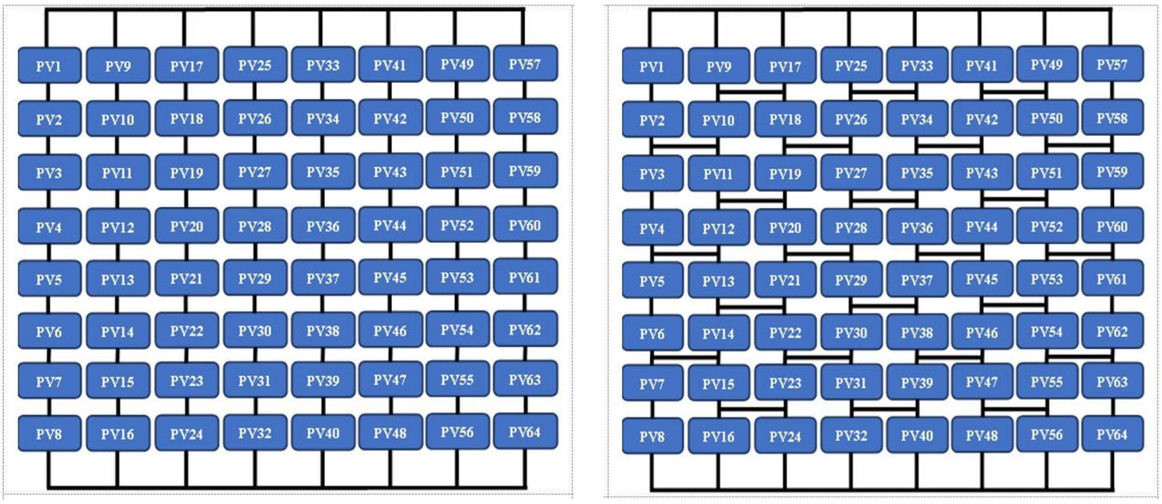
The S-P setup is commonly used in PV systems because of its straightforward design and absence of extra connections. However, it is very prone to mismatch losses during PSCs because of the way more modules are connected in series. Each module is initially linked in series to create strings, which are then linked in parallel [19]. Blocking and bypass diodes protect the strings from short circuits and PSCs. The total output current (I_{PV}), voltage (V_{PV}), and power (P_{PV}) are calculated using (2).

$$\left.\begin{array}{l} I_{Str(1)} = \sum_{k=1}^{k=8} I_k; I_{Str(2)} = \sum_{k=9}^{k=16} I_k; I_{Str(3)} = \sum_{k=17}^{k=24} I_k; I_{Str(4)} = \sum_{k=25}^{k=32} I_k; \\ I_{Str(5)} = \sum_{k=33}^{k=40} I_k; I_{Str(6)} = \sum_{k=41}^{k=48} I_k; I_{Str(7)} = \sum_{k=49}^{k=56} I_k; I_{Str(8)} = \sum_{k=57}^{k=64} I_k; \\ I_{pv} = I_{Str(1)} + I_{Str(2)} + \ldots\ldots\ldots\ldots\ldots + I_{Str(8)} = \sum_{k=1}^{k=8} I_k \\ V_{pv} = V_1 + V_2 + V_3 + \ldots\ldots\ldots + V_8 = \sum_{k=1}^{k=8} V_k = 8V_k \\ P_{pv} = V_{pv} \times I_{pv} \end{array}\right\} \quad (2)$$

3.2. Bridge-link (B-L) configuration

Modules can be arranged like bridge rectifiers with cross ties. If some modules in the PV array experience PS, the output voltage drops significantly. In this setup, two modules are connected in series and paralleled with another pair of series modules [20]. The total output voltage is the sum of the series voltages, while the current is the sum of the parallel currents, achieving the desired output levels. The total output current (I_{PV}), voltage (V_{PV}) and power (P_{PV}) are calculated using (3).

$$\left.\begin{array}{l} I_{pv} = I_1 + I_9 + I_{17} + I_{25} + I_{33} + I_{41} + I_{49} + I_{57} = 8 \times V_k \\ V_{pv} = V_1 + V_2 + V_3 + \ldots\ldots\ldots + V_8 = \sum_{k=1}^{k=8} V_k = 8V_k \\ P_{pv} = V_{pv} \times I_{pv} \end{array}\right\} \quad (3)$$



(a) (b)

Figure 2. PV module interconnection styles, (a) S-P and (b) B-L

3.3. H-C configuration

In the H-C setup, six modules are organized in a hexagonal pattern that looks like a honeybee hive, with all hexagonal units linked by cross-ties [21]. Each hexagon is made up of two groups of three modules linked in series, and these groups are then connected in parallel. The overall output voltage and current are calculated by adding the series voltages and parallel currents. The total output current (I_{PV}), voltage (V_{PV}), and power (P_{PV}) are calculated using (4),

$$\left.\begin{aligned} I_{pv} &= I_1 + I_9 + I_{17} + I_{25} + I_{33} + I_{41} + I_{49} + I_{57} = 8 \times V_k \\ V_{pv} &= V_1 + V_2 + V_3 + \ldots\ldots + V_8 = \sum_{k=1}^{k=8} V_k = 8V_k \\ P_{pv} &= V_{pv} \times I_{pv} \end{aligned}\right\} \quad (4)$$

3.4. Proposed TCT configuration

The TCT configuration, also called the cross-tied configuration, aims to lessen the effects of PS in S-P systems. Cross-ties between modules create alternative current paths for shaded modules, removing the need for bypass diodes and avoiding hotspot problems. In this arrangement, modules are linked in rows (in parallel), and these rows are then connected in series. The TCT configuration is assessed systematically under various PSC scenarios, providing a structural mitigation approach instead of depending on dynamic electronic reconfigurations. The total output current (I_{PV}), voltage (V_{PV}), and power (P_{PV}) are calculated using (5).

$$\left.\begin{aligned} I_{pv} &= I_1 + I_9 + I_{17} + I_{25} + I_{33} + I_{41} + I_{49} + I_{57} = 8 \times V_k \\ V_{pv} &= V_{RW1} + V_{RW2} + V_{RW3} + V_{RW4} + V_{RW5} + V_{RW6} + V_{RW7} + V_{RW8} \\ P_{pv} &= V_{pv} \times I_{pv} \end{aligned}\right\} \quad (5)$$

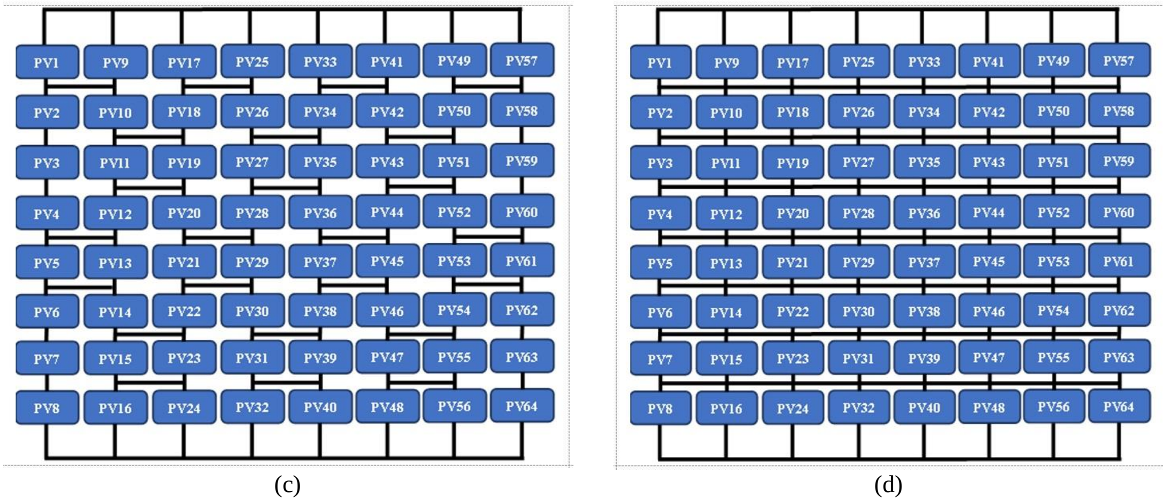


Figure 3. PV module interconnection styles, (a) H-C and (b) proposed TCT

4. PERFORMANCE PARAMETERS

The effectiveness of the suggested methods is assessed based on the following criteria.

4.1. Mismatching power

Mismatch loss occurs when solar cells or modules with varying characteristics are interconnected and subjected to different conditions. As a result, the difference in power generation between two scenarios, such as the maximum power output under ideal conditions and the reduced power output under PS, is referred to as mismatch PL:

$$P_{(\text{mismatching loss})} = P_{max}\ (\text{unshaded condition}) - P_{GMPP}\ [22] \quad (6)$$

4.2. FF

The FF is a key metric for assessing solar panel efficiency. It is determined by dividing the actual rated maximum power (Pm) by the theoretical maximum power, which is the product of the open-circuit voltage (Voc) and short-circuit current (Isc). A higher FF indicates lower losses due to internal resistances, regardless of whether the cells are connected in series or parallel:

$$\text{Fill - Factor} = \left[\frac{P_{max}}{(V_{oc} * I_{sc})}\right]\ [23] \quad (7)$$

4.3. Power losses (%)

The term refers to the ratio between the difference of the global maximum power point (GMPP) of the PV array under standard test conditions (STC) and the GMPP under partial shaded condition (PSC) to the global maximum power under STC,

$$\text{Power - Loss} = \left[\frac{GMPP_{(STC)} - GMPP_{(PSC)}}{GMPP_{(STC)}}\right] [24] \quad (8)$$

4.4. ER

It is defined as the ratio of Maximum power at global maximum power point (PGMPP) and Maximum power at STC [PSTC]. The efficiency of solar PV increases with increasing ER,

$$\text{ER} = \frac{P_{(PSC)}}{P_{(STC)}} = \left[\frac{(V_{MPP} * I_{MPP})_{PSC}}{(V_{MPP} * I_{MPP})_{STC}}\right] [25] \quad (9)$$

5. SIMULATION RESULTS AND DISCUSSIONS

The evaluation of the SP, HC, BL, and proposed TCT setups was conducted for a 335W (8×8) PV array using MATLAB. The array has a nominal voltage of 38.1 V and a current of 8.80 A. Simulations under various shading conditions assessed performance metrics like FF, Mismatching power, Power loss, and ER. The simulations were run on a MATLAB/SIMULINK platform with a Dual-Core Processor, 2.2GHz, and 8GB RAM. Specifications for the single diode PV model are in Table 1.

Table 1. Specifications of the proposed MGPGIDS Vikram solar PV module

Parameter	Values
P_{max}	335W
I_{max}	8.80A
V_{max}	38.1V
I_{sc}	9.35A
V_{oc}	46.5V

5.1. During short-wide (SW) shading conditions

The last three rows in this shading design had shading across three columns with irradiances of 600, 400, and 200 W/m^2. Figure 4 shows the partial shading. The first four columns of the fifth row were shaded at 600 W/m^2, while the rest received full irradiance of 900 W/m^2, as illustrated in Figure 4(a). Figure 4(b) shows SN, Figure 4(c) shows LN, and Figure 4(d) shows center. In this shading pattern, the performance of different PV array configurations was assessed, and the findings clearly indicate the enhanced efficiency of the suggested TCT configuration when compared to traditional S-P, B-L, and H-C setups, as presented in Table 2. The proposed TCT configuration achieved the highest GMP of 10,718 W, outperforming S-P (10,190 W), B-L (10,359 W), and H-C (10,324 W), thereby proving its enhanced capability in extracting power under PS conditions are shown in Figure 5.

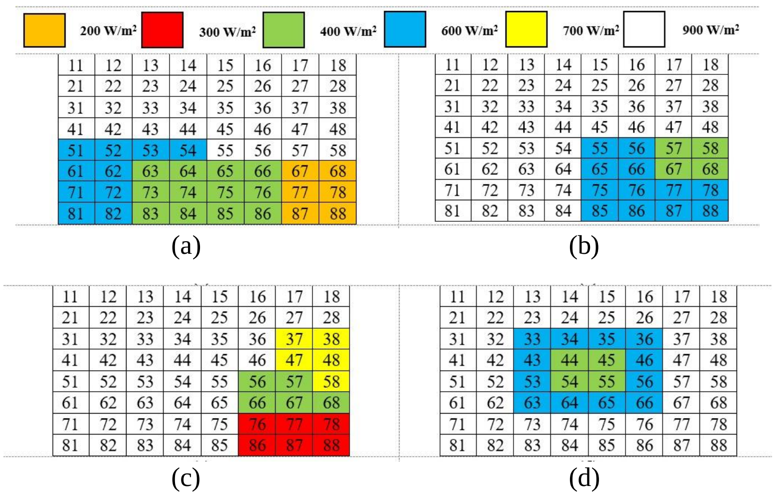


Figure 4. Partial Shading (a) SW, (b) SN, (c) LN and (d) center

Table 2. Estimation of performance indices for shade pattern (1–4)

Shadingpattern	Configuraton	GMP	Mis-matchingLoss (W)	Fill-factor(FF)	Power-Loss(PL)	Execution ratio(ER)
W	S-P	10190	9010	23.43	46.92	0.530
	B-L	10359	8841	23.82	46.04	0.539
	H-C	10324	8876	23.74	46.22	0.537
	Proposed TCT	10718	8482	24.65	44.17	0.558
SN	S-P	15285	3915	35.15	20.39	0.796
	B-L	15476	3724	35.59	19.39	0.806
	H-C	15438	3762	35.50	19.59	0.804
	Proposed TCT	16066	3134	36.95	16.32	0.836
LN	S-P	14572	4628	33.51	24.10	0.758
	B-L	15035	4165	34.58	21.69	0.783
	H-C	14863	4337	34.18	22.58	0.774
	Proposed TCT	15450	3750	35.53	19.53	0.804
Center	S-P	15823	3377	36.39	17.58	0.824
	B-L	15978	3222	36.75	16.78	0.832
	H-C	16134	3066	37.10	15.96	0.840
	Proposed TCT	16641	2599	38.27	13.32	0.866

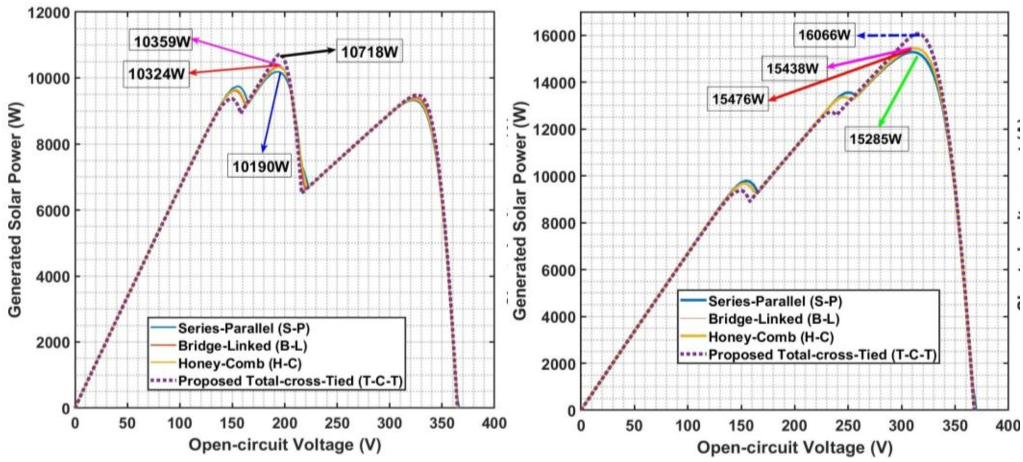


Figure 5. PV characteristics under SW and SN pattern

Additionally, it recorded the lowest mismatch loss at 8,482 W, underscoring its efficiency in minimizing energy disparities caused by uneven irradiance. The FF for the TCT configuration was also the highest at 24.65, reflecting improved conversion efficiency of solar energy. In terms of power loss, the TCT configuration exhibited the lowest percentage at 44.17%, significantly better than that of S-P (46.92%), B-L (46.04%), and H-C (46.22%). This reduction in power loss indicates decreased energy wastage. Moreover, the ER is a measure of the configuration's operational reliability and it was also highest for the TCT setup at 0.558, further validating its superior performance under shaded conditions.

5.2. During short-narrow (SN) shading conditions

The shaded areas of the column and row have lower irradiance levels of (600, 400) W/m^2, while the rest of the panel reaches a maximum of 900 W/m^2, as shown in Figure 4(b). In accordance with this shading pattern, the efficacy of various PV array configurations, including S-P, B-L, H-C, and the newly proposed TCT, was comprehensively assessed in Table 2. The P-V characteristic curves illustrated in Figure 5 clearly indicate that the TCT configuration yields the highest power output of 16,066 W, surpassing the outputs of S-P (15,285 W), B-L (15,476 W), and H-C (15,438 W). This indicates a more effective energy harnessing capacity even when parts of the array are shaded. The TCT layout also exhibits the lowest mismatch loss at 3,134 W, which is significantly less than those of the other configurations, showcasing its strength in minimizing power losses due to non-uniform irradiance.

Correspondingly, the power loss percentage was lowest for the TCT configuration at 16.32%, compared to 20.39% for S-P, 19.39% for B-L, and 19.59% for H-C which is indicating better energy retention and reduced wastage. Furthermore, the ER, which gauges both effectiveness and operational reliability, also peaked at 0.836 for the TCT configuration. This underscores its resilience and consistent performance under challenging environmental conditions.

5.3. During long–narrow (LN) shading conditions

The shading pattern uses four distinct irradiation profiles: (900, 700, 400, and 300) W/m², as shown in Figure 4(c). The TCT PV array setup exhibits the highest efficiency and reliability under this shading pattern. As shown in Figure 6, TCT achieves a peak power output of 15,450 W, outperforming S-P at 14,572 W, B-L at 15,035 W, and H-C at 14,863 W. This indicates TCT's superior capability to harness solar energy in shaded conditions. Additionally, TCT has the lowest mismatch loss at 3,750 W, significantly better than S-P (4,628 W), B-L (4,165 W), and HC (4,337 W). Lower mismatch loss translates directly to more consistent and stable power generation under PS conditions. Furthermore, the TCT configuration has the highest FF of 0.804, indicating greater efficiency in converting available solar energy into usable electricity. It also shows the lowest power loss percentage (19.53%), further affirming its effectiveness in reducing energy waste.

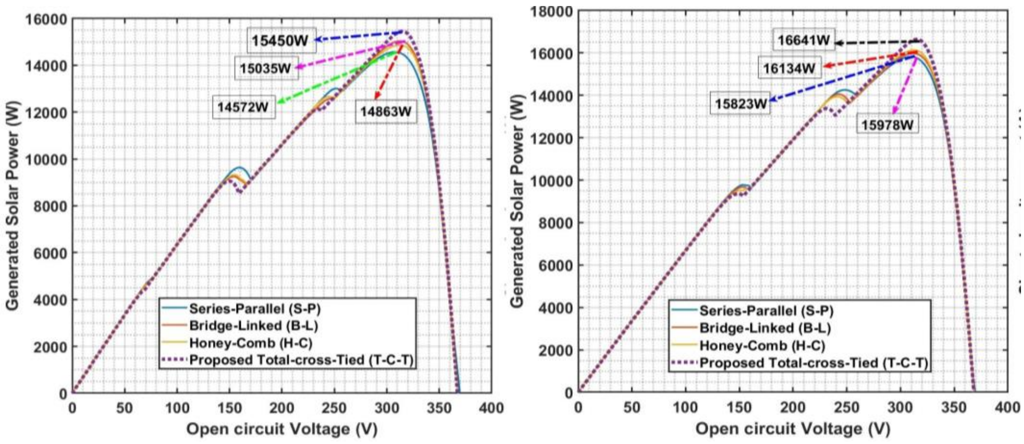


Figure 6. PV characteristics under LN and center pattern

5.4. During center shading conditions

The shading area has a consistent irradiance of 900 W/m² in the first and last two rows. The 3rd and 6th rows receive 600 W/m² and 900 W/m², respectively, while the 4th and 5th rows experience 400 W/m² and 900 W/m², as shown in Figure 4(d). The TCT PV array setup demonstrates the best performance under this shading pattern, achieving a peak power output of 15,450 W, which exceeds S-P's 14,572 W, B-L's 15,035 W, and H-C's 14,863 W. This indicates TCT's superior capability to harness solar energy in shaded conditions. Additionally, TCT has the lowest mismatch loss at 3,750 W, outperforming S-P (4,628 W), B-L (4,165 W), and H-C (4,337 W). Lower mismatch loss results in more reliable power generation during PS. The TCT setup boasts the highest FF of 0.804, indicating greater efficiency in converting solar energy to electricity, along with the lowest power loss percentage of 19.53%, highlighting its effectiveness in reducing energy waste.

6. CONCLUSION

The TCT method was introduced in this paper as a new strategy to boost PV array efficiency under PS. Findings revealed that the TCT layout outperformed traditional configurations like S-P, B-L, and H-C in power generation, mismatch loss, power loss percentage, FF, and ER. This highlights the TCT configuration's ability to ensure efficient energy output and reliability in fluctuating irradiance without the need for complex adjustments or extra hardware. Future research may explore intelligent MPPT techniques, real-time validation, and scalability assessments to enhance the practicality of TCT systems in larger solar installations.

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The authors confirm the research was conducted independently and without financial influence.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Sudhakaran Mahalingam		✓			✓	✓					✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing **- O**riginal Draft
E : Writing **-** Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no financial conflicts or personal relationships that could have influenced this work.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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