Analysis and Comparison of Various Photovoltaic Array Configurations under Partial Shading Conditions

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Abstract: Partial shading situations are one of the main problems limiting photovoltaic (PV) array power generation. It may result in module mismatch, which could have negative consequences including reduced power output and hot spots. Factors such as passing clouds, tree shadows, surrounding buildings, towers, poles, etc., all contribute to partial shading. Consequently, the power output is lower than anticipated. It is dependent on the PV array configuration as well as a number of shaded modules. This paper analyzed two array PV configurations: the series-parallel (SP) configuration and total- cross-tied (TCT) configuration under partial shading conditions. Two configurations were evaluated in this research: SP and TCT. This experimental study created and studied SP and TCT configurations of 3 series by 3 parallel (3s3p sized) under varying partial shading patterns. Performance for each pattern was assessed using both configurations. The measured solar irradiation was 900 W/m2. According to the results, the TCT setup performs better than SP configuration in partial shading conditions, as TCT configurations offer more current routes than SP configurations, which reduces power losses because they have more internal connections than SP configurations.

Keywords: Array PV, Partial shading conditions, Photovoltaic, Series-parallel configuration, Total-cross-tied configuration.

INTRODUCTION

Global energy demand is rising in tandem with the global population. The majority of the world's energy needs are met by fossil fuels. However, fossil fuels are depleting, and their environmental impact is growing by the day. As a result, using of energy from renewable sources, particularly solar energy or photovoltaics (PV), is becoming more common (Berdysheva and Ikonnikova, 2021). Solar energy is free, pollution-free, low-maintenance, dependable, and unlimited. But there are several drawbacks, such as a costly installation fee and poor effectiveness in converting energy (Kumar *et al.*, 2023). PV cells generate solar energy electricity. It has a maximum power point (MPP) based on its power-voltage (P-V) feature and an irregular current-voltage (I-V) characteristic (Gohar *et al.*, 2020). Solar irradiation and temperature have an impact on the power output of a PV module. Operating the PV modules at the maximum power point (MPP) is necessary to enhance their efficiency (Zhang *et al.*, 2019). One of the key factors affecting PV module efficiency is partial shading (PS). There are multiple factors that might generate partial shading, including clouds, structures, trees, and snow (Maharana *et al.*, 2021). When partial shading occurs, the PV modules within the system experience varying levels of solar radiation. As a result, the power-voltage (P-V) and current-voltage (I-V) characteristics of the PV array exhibit multiple peaks, leading to power dissipation in the system. One of the approaches to mitigate power losses is by implementing PV array configuration schemes (Bingöl & Özkaya, 2018). Modeling, simulation, and mathematical analysis have been used to accomplish the majority of PV array configuration studies. Using various experimental patterns, this study examines the SP and TCT configurations under partial shadowing conditions.

In order to reduce partial shading losses, El-Dein *et al.* (2013) proposed a novel mathematical

model for selecting the optimum configurations of a PV array as a mixed-integer linear programming problem. Half reconfigurable PV arrays, full reconfigurable PV arrays, and TCT are used to link PV modules to create a PV array. The proposed reconfiguration lowers partial shade losses, the researchers found after comparing the outcomes of different configurations. Rao *et al.* (2014) suggested a fixed interconnection technique for PV arrays to improve PV efficiency in instances of partial shadow. The 3 by 3 PV array was used to achieve the suggested strategy. The suggested scheme's outcomes were contrasted with those of the SP, TCT, and BL configurations. On a 6x4 PV array, Belhachat and Larbes (2015) examined the outcomes of the S (Series), P(Parallel), SP (Series-Parallel), TCT (Total Cross Tied), BL (Bridge Link), and HC (Honey Comb) designs using every conceivable shading condition. It was done using the Bishop photovoltaic module model. The acquired findings showed that in the majority of PSC scenarios, the TCT arrangement offered the best performances. Malathy and Ramaprabha (2015) examined the efficiency of a number of PV array sizes and shading schemes. A new configuration, S, P, SP, TCT, HC, and BL were also suggested. In terms of maximum power, the new design performed better than the TCT setups. A brand-new technique for predicting module connections in a PV array using a TCT layout was put up by Pareek and Dahiya (2016). The new approach arranges the shaded and un-shaded modules in the array so that the shading effects are equally spread throughout each row. The investigation is conducted under a variety of shadowing conditions. The findings demonstrate that the technique offers several options for reconfiguring PV arrays to enhance PV array performance. Using 14 shading scenarios, Bana and Saini (2017) proposed a novel PV array configuration. The output power of a novel PV array configuration is compared to the output power of SP, TCT, BL, and HC configurations.

Partıal Shadıng Effect on Solar Cells

Ensuring constant and uninterrupted lighting for photovoltaic (PV) panels can be challenging due to various factors, such as shadows caused by construction or trees, changes in weather conditions, presence of clouds, and the daily variation in the angle of the sun, as depicted in Figure 1. These factors can lead to power losses resulting from shadows, as well as current and voltage mismatches within and between PV strings.

Typically, PV modules are equipped with bypass diodes to mitigate losses caused by shaded cells (Djalab, *et al.*, 2018). A cell may be thought of in this setting as combining a current source with a diode. The photocurrent moves in the opposite direction through the diode. Because of this, if one cell in the string is partly shaded, it will provide less current than every other cell in that string, and the other cells will try to make up for this deficit by delivering more current. Due to the cell's behavior as a diode in reverse bias, this adjustment is, however, not practicable. As a result, the current generated by the cell in the shaded area will restrict the string's total current (Mahela & Shaik, 2017).

A bypass diode is linked between a series-connected string of each cell in order to solve this problem. The current can only travel in one way thanks to the bypass diode. Whenever power passes through the parallel-connected bypass diode, it provides a path of minimum impedance. This prevents power losses in the panel and helps prevent issues such as hotspots and module cracking (Ahmad, *et al.*, 2017).



Plate 1. Partial shading on the PV Panel

Types of solar array configuration

Experimentation in (Pareek & Dahiya, 2014) shows that when correct or suitable PV module configurations are implemented while considering respective scenarios, more power can be generated at the output of solar PV modules. When the PV modules are connected in series, the open-circuit voltage increases, while connecting in parallel increases the short-circuit current. As a result, solar PV systems employ various configurations to achieve the desired voltage and current levels at the output (Samantaray & Sasmita, 2016). Furthermore, due to the ties connected between the strings of the PV modules, TCT, BL, and HC are commonly known as cross ties configurations.

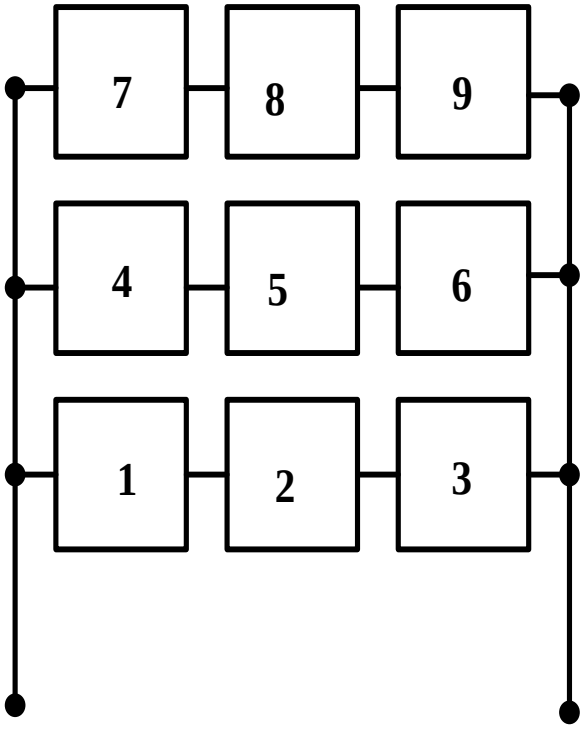

Fig 1 Series parallel configuration

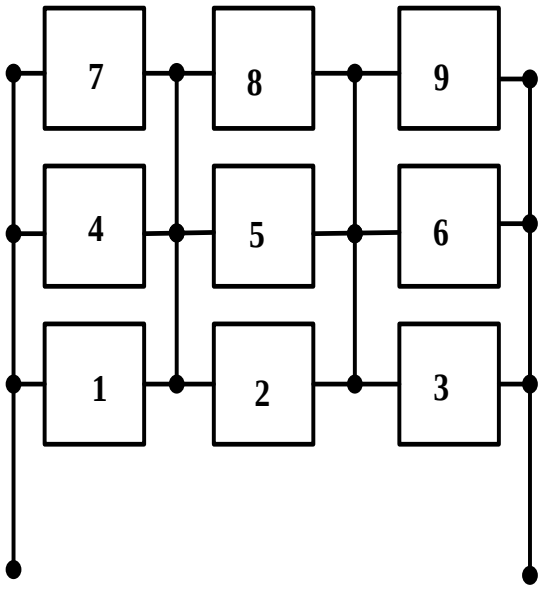

Fig. 2. Total cross Tied Configuration

METHODS

The research conducted was experimental in nature, utilizing a 3s3p array comprising nine modules obtained. Two different PV array configurations, namely series-parallel (SP) and total-cross-tied (TCT), were created for the experiment. Measurements were carried out under identical conditions for both the SP configuration and the TCT configuration. Solar irradiation, power output, voltage output, and current output were among the output parameters that were examined. The diagram that is presented below clearly outlines the experimental process. The experiment took place at the Department of Physics with Electronics, School of Applied Sciences, Nuhu Bamalli Polytechnic Zaria.

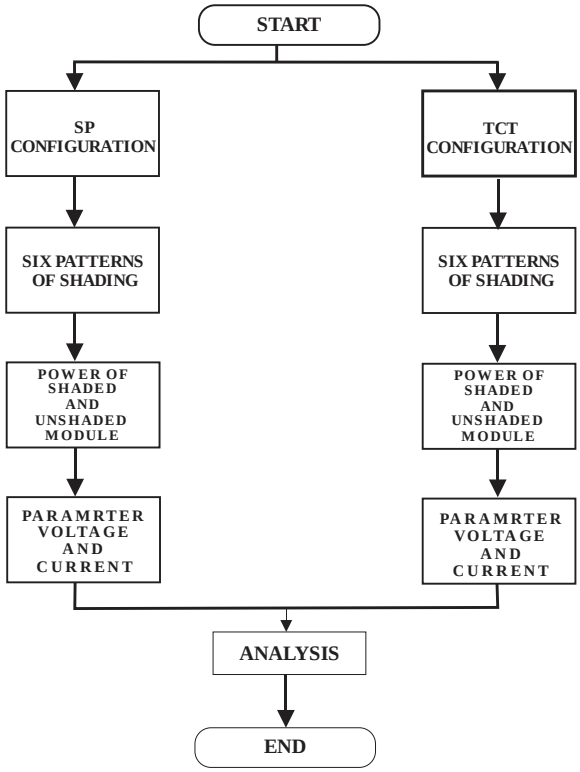

Fig. 3. Experimental procedure

PV Module

The data regarding the PV module was obtained from the datasheet of a 100-watt PV panel, as shown in Table I. Under normal operating conditions, the bypass diode does not have any active role. However, in the event of shading on

the PV panels, a portion of the series current will flow through the bypass diode, while the remainder will pass through the shaded solar cell. Each module is equipped with either two bypass diodes or one bypass diode for every 18 solar cells. Bypass diodes are of utmost importance for the outcomes of photovoltaic power plants.

Table 1. Manufacturer's PV module rating

Specification	Value
Manufacture	Felicity
Max power	100W
Open circuit voltage	21.6 V
Nominal voltage	17.5 V
Nominal current	5.72 A
Short circuit current	6.46 A
Number of cell	36
Cell type	Monocrystalline silicon

Shading Patterns

To attain the best research conditions in SP, TCT, and BL configurations during partial shading conditions, it is important to investigate various conditions to learn about the Performance traits of these configurations. The shading pattern is simulated by blocking the PV surface with paper. Five concepts make up the partial shading condition experiment. A single PV module was shaded by the 1st pattern. In the 2nd pattern, two modules are shaded consecutively. A row of three modules was darkened in the 3rd pattern. In the 4th pattern, 2 PV modules were darkened in a column. In the 5th pattern, three PV modules was darkened in a column. The 6th pattern 3 PV modules were darkened diagonally/stepwise. In all these shading conditions the open-circuit voltage, open-circuit current, and the maximum power produced by the array were recorded.

RESULTS AND DISCUSSION

Table 2. Result of SP Configuration

PATTERN	VOLTAGE (VOLTS)	CURRENT (AMPERE)	POWER (Watts)
I	53.01	12.72	674.2
II	51.72	12.99	672.2
III	51.59	12.90	665.6
IV	53.63	10.39	557.5
V	55.77	8.08	451
VI	56.09	8.03	450.6

Table 2 displays the electrical characteristics of the SP setup under different partial shade conditions It is clear that there is a connection between the electricity generated and the shading patterns The power generated was low as a result of the high power losses caused by more shaded modules On the first pattern the most power was produced A single module PV was covered blocking 674 2 W/m2 The fifth and sixth patterns produced the least power When three PV modules were shaded in a column and diagonally it was 451 W/m2 and 450.6 W/m2. Despite the fact that the third pattern featured three shaded modules the loss was minimal because they were connected in series The first pattern produced the highest power production compared to the others

since only one module was shaded even when 2 PV modules were darkened in the 2nd pattern and the 4th pattern. This is because of the bypass diode's current flows resulting in little power losses.

Table 3. Result of TCT Configuration

PATTERN	VOLTAGE (VOLTS)	CURRENT (AMPERE)	POWER (Watts)
I	52.96	13.46	712.9
II	52.45	13.08	686.3
III	51.40	12.95	665.7
IV	54.53	10.79	588.7
V	56.05	8.04	450.8
VI	51.82	12.83	665.2

Table 3 displays the electrical properties of several TCT configurations under partial shade conditions. As can be observed, the first pattern produced the highest power at 712.9 W/m2. The fifth pattern produced the least amount of electricity, 450.8 W/m2. Pattern four exhibited lower power generation compared to pattern two, where the darkened modules were arranged in series. When comparing patterns two, three, four, and five in the TCT arrangement to the corresponding patterns in the SP configuration, the power generated was nearly equal. However, a notable difference was observed in the sixth pattern, where the TCT configuration produced more power than the SP configuration.

In contrast to the SP arrangement, which experiences losses due to current flowing over a high resistance and lacking an ideal connection, the TCT configuration provides an optimal path for current flow, resulting in a higher power output. The presence of additional internal connections in the TCT configuration enables more current paths and minimizes power losses, leading to a more stable power output. For a extensive analysis of the power generation between the SP design and the TCT design, refer to Figure 2.

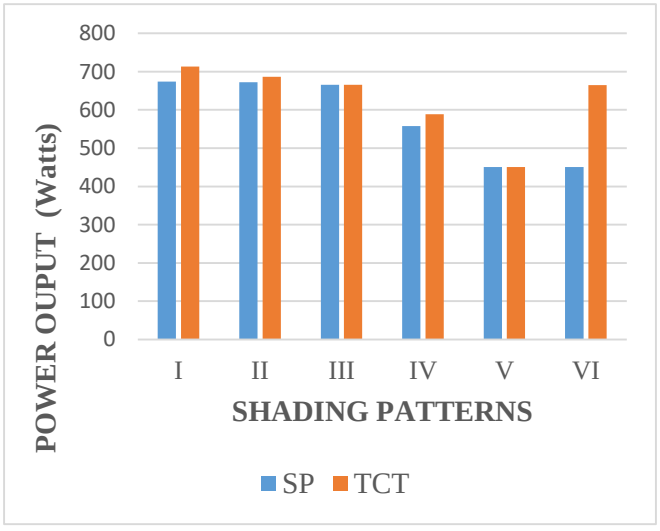

Fig. 4. The analysis of power generation between SP and TCT design

CONCLUSION

An investigation was conducted through field experiments to analyze the performance of two configurations, SP (Series-Parallel) and TCT (Total Crosstie), under partial shade conditions. The findings clearly indicate that the extent of partial shading significantly affected the electricity generation. As shading increased on

the modules, the amount of electricity produced decreased accordingly.

A comparison of the SP and TCT topologies, focusing on their impact on the PV power output of the array under partial shade conditions, is illustrated in Figure 4 with SP configuration having power outputs of 674.2, 672.2, 665.6, 557.5, 451 and 450.6watts/m^2 for patterns I, II, III, IV, V and VI respectively. While TCT configuration having power outputs of 712.9, 686.3, 665.7, 588.7, 450.8 and 665.2watts/m^2 for patterns I, II, III, IV, V and VI respectively. The results and analysis demonstrate that the TCT configuration outperforms the SP configuration. This superiority can be attributed to the presence of additional cable connections in the TCT setup, which provide more current paths. Consequently, the TCT configuration effectively prevents a decrease in current and leads to better overall performance.

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