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Comparative Analysis of Various Reconfiguration Techniques for Partial Shading Conditions in Solar Photovoltaic Systems

M. Devisridhivyadharshini[1], B. Guru Karthik Babu[2], D. Prince Winston[3] and G. Sakthivel[4]

[1, 2, 3, 4] *Department of Electrical & Electronics Engineering, Kamaraj College of Engineering & Technology, Virudhunagar, Tamil Nadu.*

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Abstract - This project presents a comprehensive comparison of voltage, current, power, and fill factor for three different photovoltaic array reconfiguration techniques: Series-Parallel (SP), Total Cross-Tied (TCT), and Hybrid TCT-SP. The study investigates the performance of these techniques under various partial shading conditions. The focus is on identifying the most effective method for power enhancement in photovoltaic arrays subjected to shading. Experimental results demonstrate that the hybrid TCT-SP reconfiguration technique consistently outperforms the SP and TCT techniques across eight different shading conditions. The hybrid technique exhibits superior power enhancement capabilities, as evidenced by increased voltage, current, power, and fill factor. This research provides valuable insights for optimizing the performance of photovoltaic arrays under partial shading conditions, contributing to the advancement of renewable energy systems.

***Key Words*:** Photovoltaic array, Series-Parallel, Total Cross-Tied, Power enhancement, Renewable energy systems.

1. INTRODUCTION

In today's era of rapidly depleting fossil fuel resources and growing concerns over climate change, renewable energy sources have emerged as promising alternatives to meet the world's energy demands sustainably. Among these, solar energy stands out as one of the most abundant and environmentally friendly resources. Solar photovoltaic (PV) technology, in particular, has gained significant attention due to its ability to directly convert sunlight into electricity [1]. As a clean and renewable energy source, solar PV systems play a crucial role in reducing greenhouse gas emissions and mitigating climate change while promoting energy independence.

Solar photovoltaic (PV) technology harnesses the energy from sunlight using photovoltaic cells, commonly made of semiconductor materials like silicon [2]. When sunlight strikes these cells, it excites electrons, creating an electric current. The generated electricity can be used directly, stored in batteries, or fed into the grid for wider distribution. PV systems can be deployed in various scales, from small residential installations to large-scale solar farms, making them versatile solutions for both centralized and distributed power generation.

Despite the numerous advantages of solar PV technology, shading remains a significant challenge that can severely impact system performance and efficiency [3]. Shading occurs when objects such as buildings, trees, or clouds obstruct sunlight from reaching certain parts of the PV array. This can lead to reduced output power, mismatch losses, and even potential hotspots in the shaded cells. Shading effects are particularly pronounced in urban environments, where buildings and other structures cast shadows on PV arrays throughout the day [4]. Additionally, seasonal changes in the sun's position and variations in weather conditions further exacerbate shading effects, making it a complex and dynamic issue to address [5]. Efficient management of shading is crucial for maximizing the energy yield and reliability of solar PV systems, especially in regions prone to partial shading conditions [6].

2. Causes of Partial Shading

Partial shading in photovoltaic (PV) systems can be caused by various factors, ranging from natural elements to man-made structures [7]. Understanding these causes is crucial for effectively managing shading effects and optimizing the performance of solar PV installations. Here are some common causes of partial shading.

2.1. Obstacles and Structures:

Buildings, trees, utility poles, and other nearby structures can cast shadows on PV arrays, leading to partial shading. The position and height of these obstacles determine the extent of shading and its impact on the array. Tall buildings or trees can cast long shadows, while shorter structures may cause localized shading on specific portions of the array.

2.2. Cloud Cover:

Passing clouds can cause intermittent shading of PV arrays by blocking sunlight. While clouds do not completely obscure the sun, they can reduce the intensity of sunlight reaching the PV modules, resulting in fluctuations in energy production. Cloud shading effects can vary in intensity and duration, depending on cloud type, thickness, and movement.

2.3. Topography:

Terrain features such as hills, mountains, or nearby structures can influence shading patterns on PV arrays. In hilly or mountainous regions, shadows cast by elevated terrain can affect the performance of solar installations, especially during early morning or late afternoon when the sun is lower on the horizon. Similarly, nearby structures or hillsides can cast shadows on PV arrays, particularly in installations located in valleys or urban areas.

2.4. Vegetation Growth:

Trees, bushes, and other vegetation can cause shading as they grow taller or denser over time. In residential or rural settings, overhanging branches or foliage can obstruct sunlight from reaching parts of the PV array, reducing energy production. Periodic pruning or trimming of vegetation may be necessary to minimize shading effects and maintain optimal performance.

2.5. Seasonal Changes:

Seasonal variations in the sun's position relative to the Earth can lead to changes in shading patterns on PV arrays. During winter months, the sun's lower angle in the sky can result in longer shadows cast by nearby structures or vegetation. Conversely, in summer, the sun is higher in the sky, reducing shading effects but potentially increasing the risk of inter-row shading in large-scale solar installations.

2.6. Dust and Dirt Accumulation:

Accumulation of dust, dirt, or debris on PV modules can create localized shading and reduce the efficiency of solar cells. Dust buildup, particularly in arid or dusty environments, can block sunlight from reaching the cell surface, leading to decreased energy output [8]. Regular cleaning and maintenance of PV modules are essential to minimize shading losses and ensure optimal performance.

By identifying and addressing these various causes of partial shading, PV system designers and operators can implement effective strategies to mitigate shading effects and maximize energy yield from solar installations.

3. Consequences of Partial Shading in PV Performance

Partial shading can have significant consequences on the performance of photovoltaic (PV) systems, leading to reduced energy production, efficiency losses, and potential damage to PV modules [9]. Here are some of the key consequences of partial shading:

3.1 Reduction in Energy Output:

One of the most immediate consequences of partial shading is a decrease in the energy output of the PV system. Shaded cells generate less electricity compared to unshaded cells, leading to an overall reduction in power production. The extent of energy loss depends on the severity and duration of shading, as well as the configuration and size of the PV array.

3.2 Mismatch Losses:

Partial shading can cause mismatch losses within the PV array, where shaded cells operate at different points on the current-voltage (IV) curve compared to unshaded cells. This results in a decrease in the overall power output of the array due to current mismatch and reduced fill factor. Mismatch losses can significantly impact the efficiency of the PV system, particularly in scenarios with uneven shading distribution.

3.3 Hotspot Formation:

Shaded cells in a PV array can act as receivers rather than generators of electrical current, leading to localized heating known as hotspots. Hotspots pose a risk of damaging the affected PV cells and can ultimately lead to module degradation or failure. Continuous exposure to hotspots can reduce the reliability and lifespan of PV modules, compromising the long-term performance of the system.

3.4 Voltage Instabilities:

Partial shading can cause voltage instabilities within the PV system, particularly in configurations where multiple strings or modules are connected in series. Shaded cells operating at lower voltages can drag down the voltage of the entire string, leading to voltage drops and fluctuations. Voltage instabilities can affect the stability of the system and may require additional control mechanisms to mitigate their impact.

3.5 Increased Degradation:

Shaded cells are subjected to higher levels of stress compared to unshaded cells, which can accelerate their degradation over time. The intermittent shading and non-shading cycles experienced by shaded cells can lead to increased mechanical and thermal stresses, potentially reducing the lifespan of the PV modules. This accelerated degradation can result in decreased energy production and increased maintenance costs over the lifetime of the PV system.

3.6 Impact on System Economics:

The consequences of partial shading can have significant economic implications for PV system owners and operators. Reduced energy output, efficiency losses, and increased maintenance requirements can lower the overall return on investment (ROI) of the system. Additionally, the need for specialized shading mitigation techniques or equipment may add to the initial capital costs of the PV installation.

Understanding and mitigating the consequences of partial shading are essential for optimizing the performance and reliability of PV systems, especially in regions prone to shading conditions. Advanced shading analysis, optimized system design, and the implementation of shading mitigation strategies can help minimize the negative effects of shading and maximize the energy yield of solar PV installations.

4. Methodology

In this study, three different reconfiguration techniques are considered to mitigate the issues associated with partial shading in photovoltaic (PV) systems: Series-Parallel (SP) reconfiguration, Total Cross-Tied (TCT) reconfiguration, and Hybrid TCT-SP reconfiguration. Each technique offers unique advantages in improving the performance and efficiency of PV systems under shading conditions.

4.1 Series-Parallel (SP) Reconfiguration:

In a series-parallel combination, the panels are configured in a manner where a certain number of panels are connected in series to increase voltage, and then these series-connected sets are connected in parallel to maintain current. For instance, in a 3x3 panel configuration, three panels are connected in series vertically (forming a column), and this is repeated for three such columns. Each column's voltage adds up, while the current remains constant. Then, these three columns are connected in parallel, allowing for the combined voltage of the series-connected panels to be maintained while increasing the total current output [10]. This series-parallel configuration effectively balances the voltage and current to optimize the power output of the PV array.

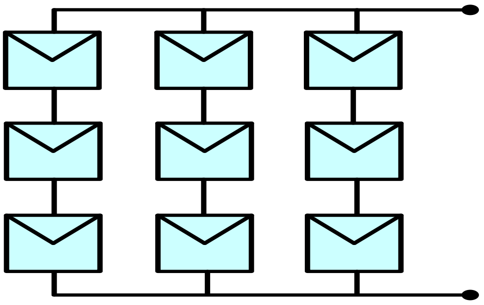

Fig -1: Series-Parallel Reconfiguration

4.2 Total Cross-Tied (TCT) Reconfiguration:

TCT reconfiguration involves interconnecting all the cells or modules in a grid-like fashion, forming a mesh network. This configuration allows current to flow in multiple directions, bypassing shaded cells and redistributing it among unshaded cells. TCT reconfiguration effectively reduces the effects of shading-induced mismatch losses. TCT reconfiguration minimizes voltage drop and increases the energy yield of the PV system under partial shading. By providing multiple current paths, it prevents hotspot formation and reduces the risk of module damage.

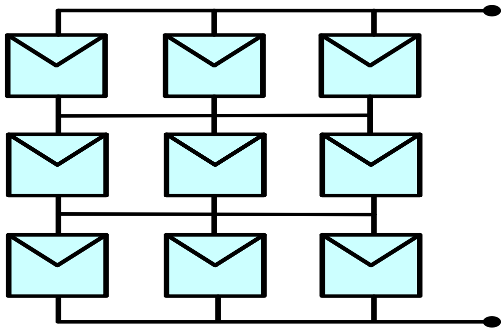

Fig -2: Total-Cross-Tied Reconfiguration

4.3 Hybrid TCT-SP Reconfiguration:

Hybrid TCT-SP reconfiguration combines elements of both SP and TCT configurations to optimize performance under partial shading conditions.
It involves dividing the PV array that the panels connected in parallel (SP configuration) and interconnecting these sub-arrays in a cross-tied manner (TCT configuration). The hybrid approach leverages the benefits of both SP and TCT configurations. It reduces mismatch losses by isolating shaded sub-arrays (SP) and redistributes current among unshaded cells (TCT). This results in improved energy yield, reduced voltage drop, and enhanced overall efficiency of the PV system under shading conditions.

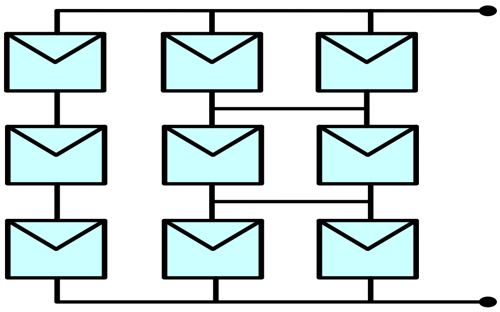

Fig -3: Hybrid TCT-SP Reconfiguration

5. Results and Discussion

Ten different Shading patterns were considered in this study which is shown in Fig. 4. These patterns represent various real-world scenarios where partial shading can occur in photovoltaic (PV) arrays.

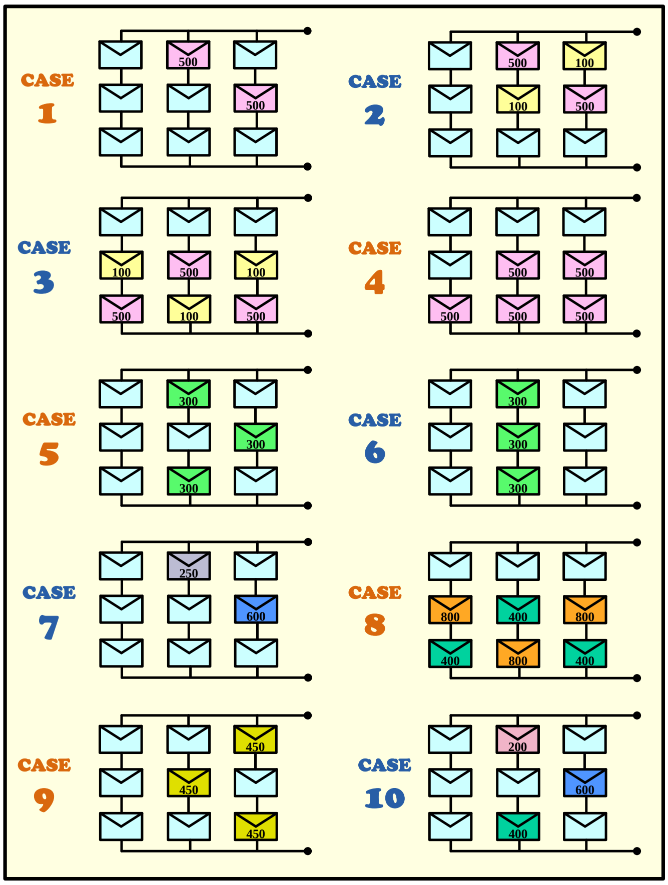

Fig -4: Shading Patterns considered in this study

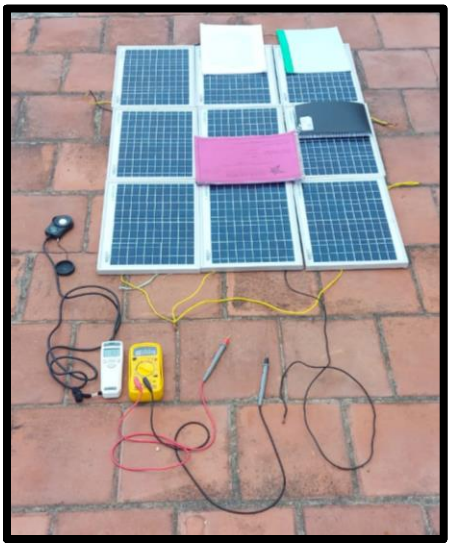

Fig -5: Experimental Setup

Through both simulation and experimental analysis, we evaluated the performance of three different PV array reconfiguration techniques: Series-Parallel (SP), Total Cross-Tied (TCT), and Hybrid TCT-SP. Figure 5 shows the Experimental setup done for this research.

Our results demonstrate that the proposed Hybrid TCT-SP configuration outperforms both SP and TCT configurations under the considered shading conditions. For eight out of the ten shading patterns studied, the Hybrid TCT-SP configuration consistently yielded higher output power compared to the other configurations. This indicates the effectiveness of the hybrid approach in mitigating the effects of partial shading and maximizing energy production in PV systems.

Table -1: Simulation Results for the Comparison of Output Power in watts

Cases	SP Config.	TCT Config.	Hybrid SP-TCT
1	60	75	75
2	12	48	48
3	9	21	24
4	45	45	45
5	48	69	69
6	69	69	69
7	55.5	67.5	67.5
8	36	48	48
9	57	73.5	73.5
10	54	66	66

The simulated and experimental results are presented in Table 1 and Figure 6 respectively. Table 1 illustrates the comparative power output of the three configurations under different shading patterns, highlighting the superior performance of the Hybrid TCT-SP configuration. Additionally, Figure 6 provides data on the output power for each shading condition and reconfiguration technique, offering quantitative insights into their performance.

The success of the Hybrid TCT-SP configuration can be attributed to its ability to combine the advantages of both SP and TCT configurations. By connecting the panels in series for the first column, the Hybrid approach ensures increased voltage. Then, by using TCT configuration for the second and third columns, it allows current to flow in multiple directions, minimizing the impact of shading.

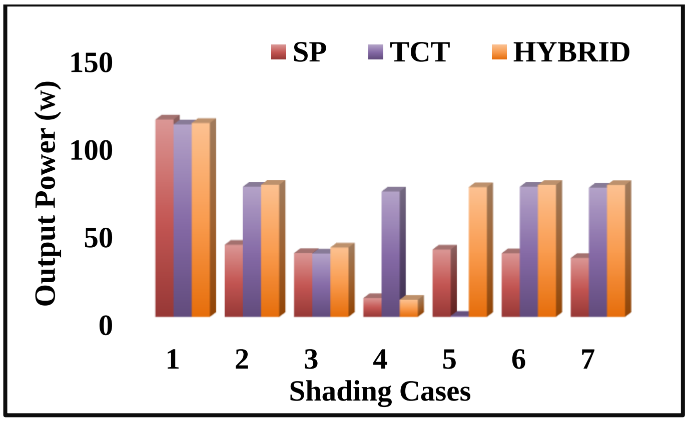

Fig -6: Experimental Results

This hybrid configuration effectively reduces mismatch losses and optimizes power distribution across the array, resulting in higher output power levels even under challenging shading conditions. These findings contribute to advancing solar energy technology, providing valuable insights for optimizing the design and operation of PV arrays.

Overall, our findings highlight the importance of selecting appropriate reconfiguration techniques to enhance the performance of PV systems under partial shading. The Hybrid TCT-SP configuration offers a promising solution for maximizing energy yield and improving the reliability of PV installations in real-world shading scenarios. These results contribute to the advancement of solar energy technology and provide valuable insights for optimizing the design and operation of PV arrays.

6. Conclusion

In conclusion, this study compared the performance of Series-Parallel (SP), Total Cross-Tied (TCT), and Hybrid TCT-SP reconfiguration techniques under ten different shading patterns. The results consistently demonstrated that the Hybrid TCT-SP configuration, which combines series connection for the first column with TCT connection for the subsequent columns, outperformed SP and TCT configurations for eight out of the ten shading conditions considered. This hybrid approach effectively mitigated the effects of partial shading, minimized mismatch losses, and maintained higher output power levels compared to traditional configurations. These findings highlight the potential of innovative reconfiguration strategies, such as the Hybrid TCT-SP configuration, to enhance the efficiency and reliability of photovoltaic systems, thereby contributing to the advancement of sustainable energy technologies.

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