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MATLAB Simulink Analysis of Switch Matrix for Optimal Solar PV Array Efficiency

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ABSTRACT

This study addresses the challenge of partial shading in solar photovoltaic (PV) systems, which limits power output in conventional configurations. To enhance efficiency, this research explores both static and dynamic reconfiguration strategies, integrating a switch matrix to adapt to diverse shading conditions. The static approach employs Sudoku puzzle pattern for matrix structuring, while the dynamic approach utilizes a controllable switching matrix within electrical array reconfiguration (EAR) to respond to environmental variability. The methodology involves simulating a 3 × 3 PV array in MATLAB Simulink to assess power optimization across varying shading scenarios. Findings reveal that incorporating the switch matrix significantly improves power output, offering valuable insights for scalable PV systems under partial shading. This work emphasizes the switch matrix's critical role in enhancing both flexibility and performance in PV arrays.

1. Introduction

The increasing importance of solar photovoltaic (PV) systems in renewable energy highlights their critical role in sustainable electricity generation. However, maximizing PV efficiency remains a challenge, particularly under partial shading conditions (PSCs). Common obstructions, such as passing clouds, nearby structures, or seasonal debris, can cast shadows on PV modules, leading to substantial irradiance imbalances [1,2]. These shading effects reduce light absorption in affected cells, decrease the output current, and thereby compromise the performance of the entire PV array. Additionally, shading may cause localized overheating, known as "hot spots," which can further damage cells and reduce the lifespan of the modules [3].

To mitigate power losses and protect shaded cells, bypass diodes are often integrated into PV systems. These diodes allow current to bypass shaded cells, minimizing overall power loss and

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reducing the risk of hot spot formation [4]. However, bypass diodes introduce additional complexity to the system by creating multiple peaks in the power-voltage (P-V) characteristics of PV arrays [5]. These multiple peaks make it difficult for traditional maximum power point tracking (MPPT) systems to locate the true global maximum, especially under complex shading patterns [6]. As a result, bypass diodes can lead to suboptimal energy extraction, limiting the effectiveness of MPPT in maintaining peak system performance [7].

Given these challenges, research has increasingly focused on methods that minimize reliance on bypass diodes by employing optimized PV array patterns and adaptable reconfiguration solutions to enhance energy capture under partial shading conditions [8]. While MPPT systems typically use converter-based algorithms to maximize power output [9,10], scaling these converters across large PV installations presents practical limitations due to high costs and operational complexity [11]. Consequently, researchers are exploring reconfiguration techniques classified into static and dynamic methods as cost-effective solutions to minimize mismatch losses and enhance energy output in partially shaded environments [12-16]. Studies have shown that these reconfiguration techniques can significantly narrow the gap between theoretical PV capacity and real-world performance, offering a promising direction for future PV system design.

Regarding basic configuration, the literature documents various PV array layouts including simple-series (SS), parallel (P), series-parallel (SP), total-cross-tied (TCT), bridge-link (BL), and honeycomb (HC) structures all with different capacities for minimizing mismatch losses [17-24]. Studies reveal that TCT and BL configurations outperform others in reducing shading-induced losses and improving reliability [25-28]. The introduction and assessment of the effectiveness of an Adaptive Cross-Tied (A-CT) configuration with a switch matrix demonstrated superiority over traditional setups through extensive analyses, achieving a power enhancement ranging from 2.71% to 6.98% under various shading conditions compared to the SP configuration [29]. Despite these advancements, the TCT configuration can still encounter performance limitations if shading affects an entire row, thereby curtailing the arrays output current [30-32]. To address such constraints, static reconfiguration techniques have been proposed. Among the widely explored methods, the Sudoku reconfiguration achieved a 10.44% improvement in maximum power output, while the Optimal Sudoku reconfiguration achieved 10.64%, both outperforming conventional TCT when a 4×4 sub-array at the center is shaded [33]. Subsequent advancements led to Advanced Sudoku [34] and Hyper Sudoku [35] configurations, which further improved shading management by refining alignment across shading levels and module orientations. Despite this significant gain, Sudoku-based configurations often require extensive interconnecting cables, leading to increased installation complexity and associated costs [36]. To enhance these benefits further, researchers have investigated optimized patterns such as non-symmetrical [37], Four-Square [38], Magic-Square [39], Dominance Square [40], and Skyscraper [41] configurations. These arrangements retain a similar structural layout while achieving greater efficiency in reducing mismatch power loss (MPL). Notably, these advanced patterns demonstrate substantial improvements in power generation by more effectively redistributing shading across rows compared to traditional TCT configurations.

Dominance Square technique enhances PV array performance but adds significant structural complexity, which complicates its application [42]. In contrast, the Skyscraper configuration yields similar benefits in MPL but relies on lengthy interconnections, which can lead to notable power losses and limit peak power output [43]. The Zig-Zag configuration, particularly under row shading conditions, offers an effective alternative by dispersing shading across the array to reduce MPL to as low as 5%, thereby significantly increasing maximum power output compared to conventional TCT [44]. Similarly, the Addition Progression Structure configuration arranges modules in a progressive pattern without altering their interconnections, resulting in MPL reductions of 11.6% to 38.3% and increasing maximum power output by approximately 1% to 38% across varying shading conditions [45]. Innovative design approaches inspired by gaming strategies are demonstrated in the chessboard configuration [46], which is particularly noteworthy for its ability to mitigate power losses across various shading conditions. This configuration achieves reductions of approximately 22.7% to 43.7% compared to TCT and 25% to 42.3% lower than SP. Similarly, the 8 Queens configuration [47] consistently shows lower mismatch power losses when compared to TCT, with reductions ranging from 3.42% to 22.74%. This indicates its effectiveness in minimizing power losses across various shading conditions. The suggested Magic Matrix Shifting (MMS) technique outperformed TCT in different shading scenarios [48]. The range of percentage reductions of MMS compared to TCT is from 28.3% to 56.7%. This indicates that under varying shading conditions, the effectiveness of the MMS design in reducing power loss varies significantly, demonstrating its potential advantages in optimizing photovoltaic systems. By optimizing PV array performance to generate more power and reduce the impact of partial shading, the Row-Constrained Swapping (RCS) configuration [49] decreases the number of shaded panels that need to be relocated by 30%, leading to an increase in overall power generation.

Dynamic reconfiguration approaches stand out for their ability to adapt in real time using a switching matrix that adjusts module connections based on current shading patterns [50,51]. The Electrical Array Reconfiguration (EAR) technique adjusts the array's topology in response to irradiance changes, enhancing power output even in shaded conditions. By modifying the electrical connections of PV modules without altering their physical arrangement, this method effectively mitigates the negative impacts of partial shading. An EAR strategy employing a controllable switching matrix has shown a 3% increase in energy output compared to static configurations [52], and an overall improvement of approximately 29% in output power relative to these static setups [53]. For instance, the study by [54] explores the practical integration of a switch matrix into a solar power system, demonstrating effective energy control in a computer-simulated reconfigurable setup connected to a small Unmanned Aerial Vehicle (UAV) propulsion system. The integration of a switch matrix with Incremental Conductance MPPT and volt-per-hertz (V/f) control effectively tackles the challenges posed by partial shading, leading to improved power extraction and enhanced overall system efficiency [55,56].

Sharma *et al.,* [14] explore strategies to address partial shading in PV systems, emphasizing that modifying the connections of solar PV sub-modules through a switching matrix can effectively reduce power loss. While these dynamic techniques offer flexibility, they often require additional components such as sensors, controllers, and switching devices, which can increase system complexity and cost. The authors [57-60] note that traditional techniques based on irradiance equalization may not yield optimal solutions under all shading conditions, indicating the need for advanced optimization methods. Integrating innovative approaches with these optimization techniques can further elevate PV array performance. An economical two-stage reconfiguration method employing a TCT configuration and a genetic algorithm demonstrated enhanced power output in extensive PV installations [61,62]. R. Kumar Pachauri *et al.,* [63] proposed Vommi Optimization Algorithm (VOA) to enhance the performance of PV systems under partial shading conditions. The algorithm optimizes the Global Maximum Power Point (GMPP) while more effectively minimizing power losses compared to traditional methods like Particle Swarm Optimization (PSO) [64,65] and TCT approach. Empirical evaluations show that VOA consistently achieves higher power outputs, with a recorded GMPP of 990W, significantly exceeding TCT performance of 862.6W and PSO performance of 956 W. These findings demonstrate the effectiveness of VOA in optimizing PV arrays under complex shading conditions. Ahmed Fathy *et al.,* [66] introduced the Honey Badger Algorithm (HBA) to effectively reduce power loss in PV arrays subjected to partial shading and random module failures, achieving output power enhancements of 7.92% to 42.18% compared to the SP configuration without reconfiguration, while outperforming traditional techniques like the Wild Horse Optimizer (WHO) [67], Artificial Gorilla Troops Optimizer (GTO) [68], and PSO in both power generation and execution time. Recent advancements have integrated predictive algorithms with optimization techniques to overcome the limitations of static and dynamic reconfigurations in PV arrays. For instance, combining genetic algorithms with TCT configurations—such as the Binary Firefly Algorithm (BFA) [69]—has demonstrated promising results in optimizing power output for large-scale PV systems. The BFA is particularly effective in selecting the switching matrix configuration that maximizes power output under varying daily conditions.

Through comprehensive analyses, the introduction and evaluation of the Adaptive Cross-Tied (A-CT) configuration utilizing a switch matrix demonstrated its superiority over conventional setups [70]. A study addressing the challenge of reduced power output in large PV plants introduced a reconfiguration approach that combines a feed-forward neural network with a switch matrix [71,72]. This method predicts shading rates, simplifies installation procedures, enhances reliability, and provides economic benefits. The implementation of relay-based switch matrices using single-pole, double-throw (SPDT) and double-pole, double-throw (DPDT) relays has proven to be a more cost-effective approach, reducing the required switch count while maintaining system reliability and optimizing operational parameters [73,74]. Calcabrini *et al.,* [75] describe a switching matrix for a 6-block module featuring 27 switches, where connections to the positive and negative terminals can be managed with a single MOSFET, while the remaining bidirectional switches are implemented using two back-to-back MOSFETs. The authors in [76] introduced a switch matrix that modifies the connections of modules within the array to achieve effective shading dispersion. This approach ensures optimal configuration of the switches, balancing the irradiance across each row of the photovoltaic array [52]. The summary of pros and cons of the PV configuration methods is shown in Table 1.

While previous studies have demonstrated the effectiveness of the static configurations [33-49] in dispersing shading to enhance power output, these setups remain labor-intensive due to the need for manual panel relocation. This limitation highlights the need for an approach that enables flexible reconfiguration without physical adjustments. Addressing this gap, the present study introduces a switch matrix to automate the Sudoku technique, allowing for electrical reconfiguration of PV panels and improved shade dispersion to maximize power output. This research expands on these developments by evaluating 3×3 PV array in MATLAB Simulink under various PSCs to assess both static and dynamic reconfiguration strategies. The findings aim to provide insights into enhancing the efficiency, reliability, and economic feasibility of PV systems under partial shading, thus contributing to scalable and resilient renewable energy technologies. The remainder of the paper is organized as follows: Section 2 outlines the methodology employed in the study; Section 3 presents the results obtained from the evaluation of the proposed approach; and Section 4 discusses the conclusions drawn from the findings.

Table 1
Summary of pros and cons of different PV configuration methods

Configuration methods	Pros	Cons
Simple-Series (SS)	- Simplest configuration, easy to implement [17].	- Highly susceptible to shading; power generation drops significantly under partial shading conditions [17].
Parallel (P)	- Reduces voltage levels, making it suitable for specific applications [18].	- Requires more cabling, which increases complexity and costs [18].
Series-Parallel (SP)	- Balances power output by combining series and parallel setups [19].	- Moderate shading resilience; still vulnerable to performance loss under partial shading [19].
Total-Cross-Tied (TCT)	- Effective in reducing shading-induced mismatch losses [25,26].	- Limited effectiveness if shading impacts an entire row, reducing output current [30,31].
Bridge-Link (BL)	- Improves reliability and shading resilience [27].	- Increases system complexity and installation cost [28].
Honeycomb (HC)	- Efficient mismatch loss reduction; suitable for partial shading [24].	- Increased cabling and setup complexity [24].
Adaptive Cross-Tied (A-CT)	- Superior power enhancement under various shading conditions, with 2.71% to 6.98% gains over SP setup [29].	- Complexity in configuration; may require additional components like switch matrices [29].
Sudoku Reconfiguration	- Reduces mismatch losses significantly; achieved 10.44% to 10.64% improvement in power output [33].	- High cabling requirements, leading to increased cost and installation complexity [36].
Advanced Sudoku/Hyper Sudoku	- Enhanced shading management; further improves alignment and power output compared to Sudoku [34,35].	- High installation complexity and cost due to increased cabling [36].
Non-Symmetrical Configurations	- Reduces mismatch losses without high interconnection requirements [37].	- Complexity in setup and design; may require unique layouts for each PV array [37].
Four-Square/Magic-Square	- Effectively reduces mismatch losses; maintains simple structural layout [38,39].	- High installation complexity; limited practical application due to intricate design [38].
Dominance Square	- Efficient mismatch loss reduction; improves overall performance [40].	- Significant structural complexity; challenging to implement practically [42].
Skyscraper	- Comparable to Dominance Square in reducing mismatch losses; good under row shading [41].	- Increased power loss due to long interconnections [43].
Zig-Zag	- Effective under row shading; reduces mismatch power losses to as low as 5% [44].	- Installation complexity; requires specific arrangement and additional cabling [44].
Addition Progression Structure	- Reduces mismatch losses by 11.6% to 38.3%; increases power output by up to 38% [45].	- Limited applicability across different shading scenarios; may need customization for different arrays [45].
Chessboard Configuration	- Reduces power losses effectively, especially under various shading conditions [46].	- Complexity in layout; may be difficult to implement in standard PV systems [46].
8 Queens Configuration	- Consistently reduces mismatch losses across shading scenarios [47].	- Limited practicality due to complex cabling and layout requirements [47].
Magic Matrix Shifting (MMS)	- Effective in reducing power losses (28.3% to 56.7%) under diverse shading conditions [48].	- Increased system complexity; may require advanced control mechanisms for optimal performance [48].

Row-Constrained Swapping (RCS)	- Decreases need to relocate shaded panels by 30%, increasing power generation [49].	- Complexity in dynamic reconfiguration; may be difficult to implement in large installations [49].
Electrical Array Reconfiguration (EAR)	- Real-time adaptability to shading changes, achieving 3% to 29% power gains over static setups [52,53].	- Requires additional components like sensors and controllers, increasing system cost and complexity [50].
Relay-based Switching Matrix	- Cost-effective solution; reduces the number of switches while maintaining reliability [73,74].	- Limited to certain configurations; complexity increases with larger PV arrays [73,74].
Switch Matrix with Algorithms (e.g., VOA, HBA)	- Reduces power losses effectively; shows superior output compared to traditional methods [63,66].	- Complexity in implementation; may require specialized knowledge to configure and optimize algorithms [63,66].
Feed-Forward Neural Network with Switch Matrix	- Predicts shading rates and simplifies installation, offering economic benefits [71,72].	- Complexity and cost due to advanced components like neural networks; requires skilled operation [71,72].

2. Methodology

In our research, we used MATLAB Simulink to simulate a 3×3 PV array system, shown in Figure 1. The main focus of our investigation was to explore different ways of rearranging the PV panels using a switch matrix inspired by problem-solving methods similar to Sudoku puzzles. To conduct a thorough analysis, we referred to the specifications of the PV panel outlined in Table 2.

The reconfiguration of PV panels employed switch matrices, as depicted in Figure 2. Each PV panel necessitated two switches for the process. In total, 18 switches (Group A Switch Matrix) were used for the 9 PV panels, employing ideal switches in Matlab Simulink for simulation. To prepare for reconfiguration scenarios, an additional 36 switches (Group B Switch Matrix) were added to redirect the circuit and improve power output during partial shading.

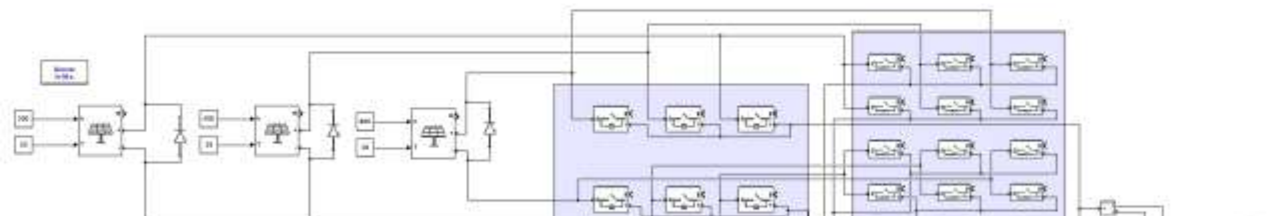


Fig. 1. Simulink-based configuration of 3×3 PV Panel Array and Switch Matrix

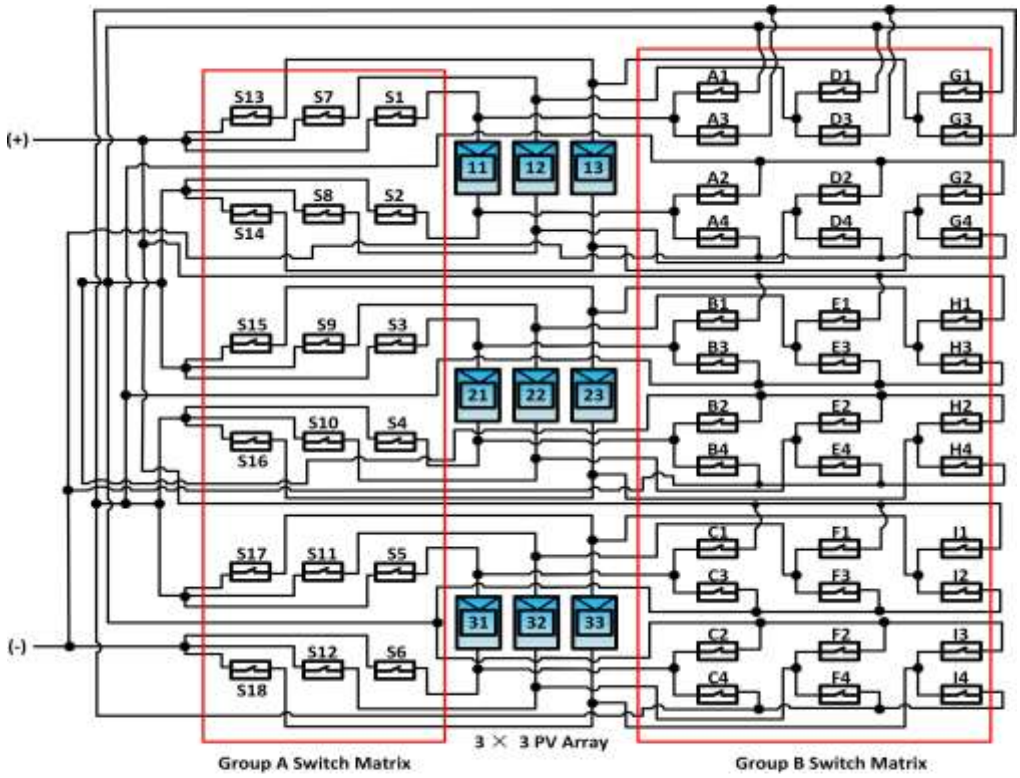


Fig. 2. Simulink-based configuration of Switch Matrix

Table 2
Matlab Simulink PV module specifications

Parameters	Specification
Open circuit Voltage, VOC	4.5 V
Short circuit Current, ISC	7.8 A
Maximum Voltage, Vm	3.6 V
Maximum Current, Im	7.4 A
Maximum Power, Pm	26.64 W
Cells per module (Ncell)	60
Temperature coefficient of VOC	-0.36099 %/°C
Temperature coefficient of Isc	0.102 %/°C

The switching configurations begin with identifying the current configuration of the PV panel array, which can either utilize the TCT or the Sudoku configuration. Following this, real-time data is collected from the system to analyze environmental conditions that may affect performance. Based on this analysis, the optimal configuration is determined to maximize power output. A decision is made regarding the switch configuration type, either activating the TCT logic or the Sudoku logic, both executed through switching systems. Once the chosen logic is in operation, the performance of the switches is continuously monitored to ensure effective functionality. Periodic maintenance checks are conducted to assess the need for any switch maintenance; if maintenance is required, appropriate actions are taken to ensure the switches are operating optimally. If no maintenance is necessary, the system continues its operation while remaining open to adjustments in configuration based on ongoing performance data. This structured approach ensures that the PV system operates efficiently, adapting to changing conditions while maintaining reliability. Figure 3 illustrates the overall process flow for managing the switching configurations.

Table 3 presents the states of Group A Switch Matrix and Group B Switch Matrix switches during TCT configuration and Sudoku reconfiguration, as illustrated in Figure 4. Our study covered four specific partial shading conditions: Random, Long, and Narrow (LN), Uneven Column (UC), and Uneven Row (UR), as illustrated in Figure 5.

In a quantitative assessment, we document the power output for each configuration under four specific partial shading conditions. This thorough analysis provides a comprehensive understanding of switch matrix-based reconfiguration strategies. These strategies, inspired by Sudoku, significantly impact the power output. The study specifically focuses on a 3 × 3 PV array system. The simulation results explain how adjusting configurations with switch matrices can improve power generation in different shading conditions. It is important to note that both TCT and Sudoku configurations use switch matrices.

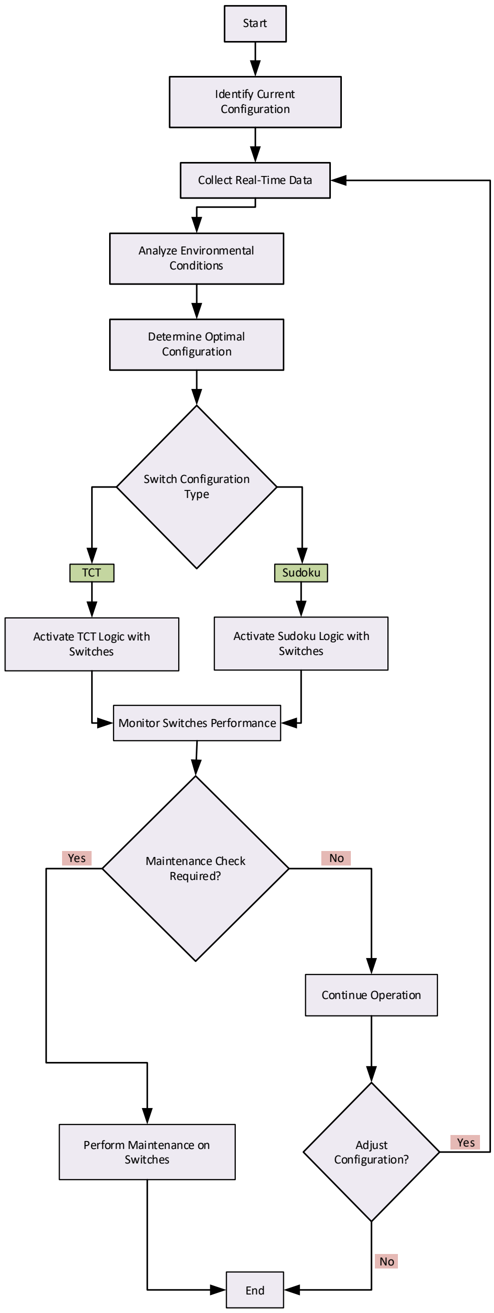


Fig. 3. Flowchart of the relay-based switching configuration process for PV arrays utilizing TCT and sudoku patterns

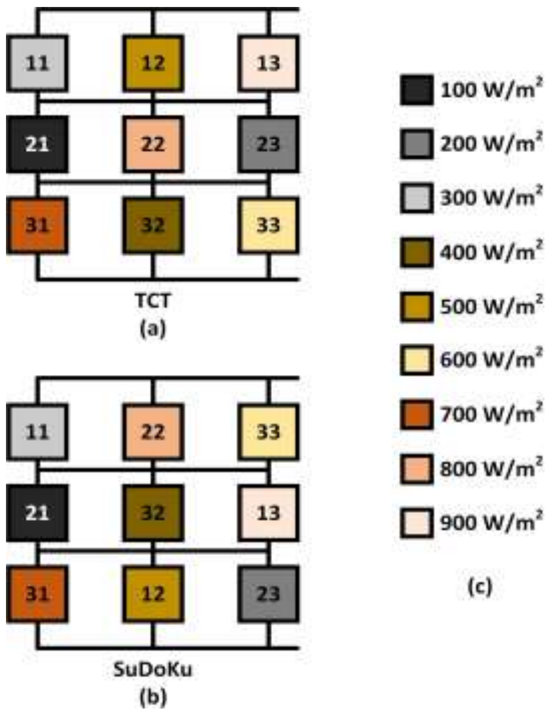


Fig. 4. (a) TCT configuration, (b) Sudoku configuration, (c) Levels of irradiance under partial shading conditions

Table 3
State of switches in Switch Matrices of 3×3 PV Panel Array with TCT and Sudoku configuration

State of switches in Group A Switch Matrix	TCT	Sudoku
S1, S2, S3, S4, S5, S6	ON	ON
S7, S8, S9, S10, S11, S12	ON	OFF
S13, S14, S15, S16, S17, S18	ON	OFF
State of switches in Group B Switch Matrix	TCT	Sudoku
A1, A2, A3, A4	OFF	OFF
B1, B2, B3, B4	OFF	OFF
C1, C2, C3, C4	OFF	OFF
E1, E2	OFF	ON
D3, D4 & F3, F4	OFF	ON
D1, D2 & F1, F2	OFF	OFF
E3, E4	OFF	OFF
H1, H2	OFF	ON
G3, G4 & I3, I4	OFF	ON
G1, G2 & I1, I2	OFF	OFF
H3, H4	OFF	OFF

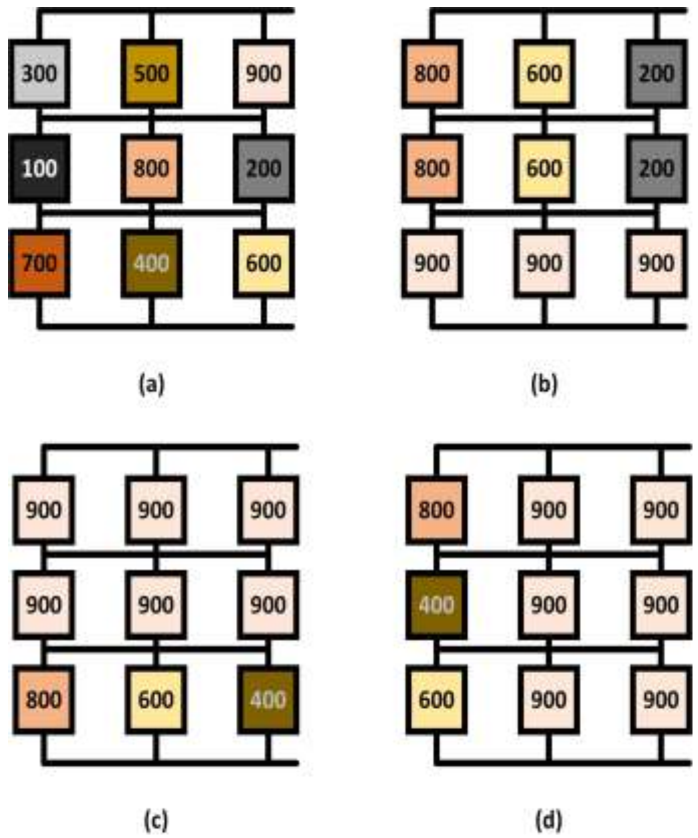
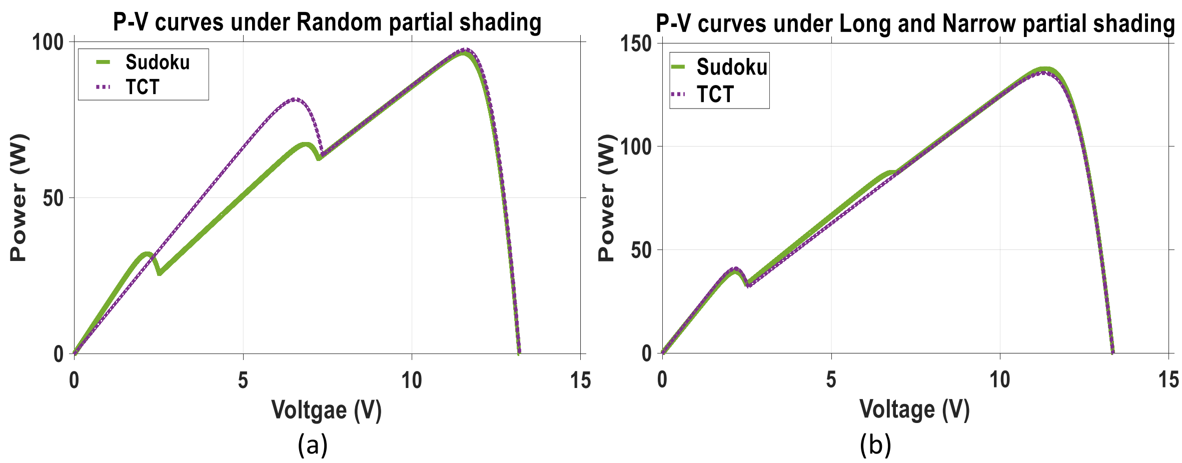
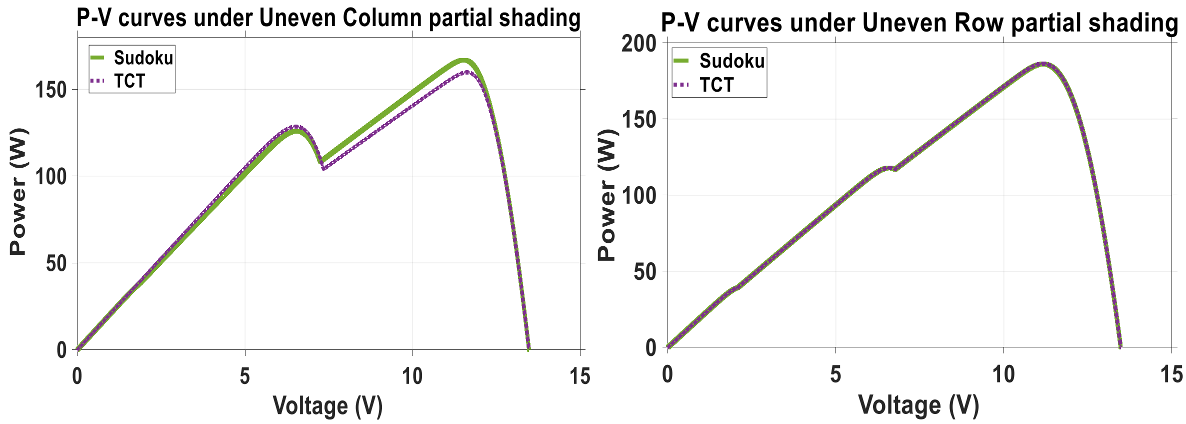


Fig. 5. Different partial shading conditions (a) random, (b) long and narrow, (c) uneven column, (d) uneven row

3. Results and Discussions

Figure 6 displays the impact of various shading conditions on the photovoltaic (PV) characteristic curves for each configuration, while Table 4 details the shading scenarios alongside corresponding power outputs. A comparative performance analysis of TCT and Sudoku configurations under different shading conditions reveals distinct advantages and limitations for each approach. Under Random partial shading, TCT achieved a higher power output of 97.41W compared to 96.36W for Sudoku, suggesting that TCT may better manage unpredictable shading. However, in the Long and Narrow shading scenario, Sudoku outperformed TCT, achieving 137.7W compared to 135.5W, likely due to the optimized layout inherent to the Sudoku configuration.





(c) (d)

Fig. 6. (a) P-V curves under random shading, (b) P-V curves under LN shading, (c) P-V curves under UC shading, (d) P-V curves under UR shading

Table 4
Maximum output power for TCT configuration and Sudoku reconfiguration under four different partial shading conditions

Configuration	Maximum Output Power (W)			
	Random	LN	UC	UR
TCT	97.41	135.5	159.7	186.2
Sudoku	96.36	137.7	166.8	186.2

In the case of Uneven Column shading, Sudoku configuration again demonstrated superior performance, generating 166.8W compared to 159.7W for TCT. Conversely, both configurations showed identical results under Uneven Row shading, each producing a power output of 186.2W, indicating that neither configuration held a distinct advantage under row-specific shading.

These findings demonstrate the importance of selecting configurations suited to specific shading conditions for optimized PV output. While TCT shows resilience to random shading, Sudoku's structured approach is advantageous in organized shading patterns, such as Long and Narrow or Uneven Column scenarios. Figure 6 visually represents these differences, while Table 4 quantitatively supports the configurations' strengths and weaknesses under various shading patterns.

Implementing Sudoku, however, involves labor-intensive manual reconfiguration. The integration of a switch matrix addresses this challenge, enabling dynamic adjustments electronically and enhancing the practicality and efficiency of Sudoku without physical repositioning. This capability is especially beneficial in scenarios where frequent shading pattern changes demand adaptable PV configurations

Further analysis suggests that TCT consistently outperforms Sudoku in random shading scenarios, consistent with findings in previous studies [38]. Sudoku, however, remains advantageous under column specific shading like Uneven Column, with comparable outcomes to TCT in row-specific scenarios. Significant differences in performance under the Long and Narrow shading condition indicate the need for further investigation to understand how variations in irradiance and array layout affect outcomes.

4. Conclusions

This comparative analysis emphasizes the critical importance of aligning photovoltaic configurations with specific shading patterns and practical implementation challenges to maximize energy output. The study highlights the unique advantages of the TCT and Sudoku configurations, demonstrating how each respond to particular shading patterns. The integration of a switch matrix notably enhances efficiency by simplifying reconfiguration processes, underscoring the potential for practical and scalable implementation. To validate the robustness of the reconfiguration strategies, future work should focus on large-scale PV arrays, particularly those with non-uniform shapes, to assess adaptability and performance. The promising results from the switch matrix in smaller arrays encourage further testing and development in diverse real-world conditions, ultimately advancing PV technology for a range of applications.

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