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OPTIMIZING POWER OUTPUT IN PARTIAL SHADING CONDITIONS: PARALLEL CONNECTED PHOTOVOLTAIC TCT (P-TCT)

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Abstract: The effective reduction of mismatch losses in photovoltaic (PV) arrays is crucial for maximizing power generation. This study introduces a novel interconnection design called "Parallel Connected Photovoltaic Total Cross Tied" (P-TCT) to address this challenge. P-TCT optimizes a PV array by splitting PV modules into parallel TCT subgroups with even number of rows and optimal parallel branching. In this investigation, twenty-four PV modules in a 4 × 6 configuration with three parallelly connected TCT subgroups were arranged. MATLAB Simulink was employed for comprehensive modelling and simulations to compare the power generation performance of PV arrays employing Series Parallel (SP), Total Cross Tied (TCT) and P-TCT interconnection. Under ideal and shadeless condition, the twenty-four-module PV arrays generated a maximum power (P_{mp}) of 3,594 W. Simulations under various random partial cloud shading scenarios revealed the P-TCT array outperformed SP and TCT. In the first random partial cloud shading scenario, the P-TCT PV array produced 2,145 W, marking a significant 36.8% and 27.1% improvement over SP and TCT PV arrays, respectively. In the second random partial cloud shading scenario, P-TCT excelled, yielding 2,197 W, a remarkable 69.9% and 58.8% increase over SP and TCT PV arrays. In summary, this research demonstrates that the P-TCT interconnection is the optimal design among the three methods, significantly improving power generation and reducing mismatch losses in PV arrays.

Keywords: photovoltaic arrays; mismatch losses; cloud shading effects; solar module interconnection; MATLAB

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1. Introduction

In recent years, research in sustainable and renewable energy sources has gained tremendous momentum. Solar photovoltaic (PV) systems have emerged as a prominent contender in the transition toward sustainable clean energy generation (Owusu & Asumadu-Sarkodie, 2016; Yang & Siaw, 2021). PV systems harness the power of sunlight to produce electricity, offering an environmentally responsible and economically feasible alternative to traditional fossil fuel based power generation (Sher *et al.*, 2021; Soomar *et al.*, 2022).

As solar energy becomes increasingly accessible across various scales, from residential installations to large-scale solar farms, it is essential to confront the challenges posed by the intermittent nature of sunlight and the complex dependency between various PV system components (Albadi, 2019; Niazi *et al.*, 2019; Yin *et al.*, 2020). The configuration and interconnection of PV modules, inverters, and energy storage solutions significantly influence a system's ability to efficiently harvest energy, mitigate losses due to shading and mismatch, and adapt to changing environmental conditions (Alahmad *et al.*, 2012; Bassi *et al.*, 2019; Das *et al.*, 2017; Niazi *et al.*, 2019; Ali *et al.*, 2023).

However, the effectiveness and overall performance of solar PV systems depend on various factors, with one key factor being the design and interconnection of PV modules in the PV array (Soomar *et al.*, 2022). To fully unlock the potential of solar energy, it is essential to optimize the interconnection design of PV arrays. While the two most common interconnections for optimizing PV panels are series-parallel (SP) and total-cross-tied (TCT), there are challenges to both type of design (El-Dein *et al.*, 2012; Kurmanbay *et al.*, 2020; Narne *et al.*, 2023; Pareek *et al.*, 2017). Over the past decade, various researchers have consistently demonstrated that in worst case scenarios, SP and TCT configurations can only harness a PV array’s maximum output power in the range of 39.45% to 63.83% for SP and 53.39% to 70.68% for TCT (Mohammadnejad *et al.*, 2016; Pachauri *et al.*, 2021; Pareek *et al.*, 2017). Although TCT performs better than SP, there is still room for improvement.

Through the application of advanced modelling, simulation, and optimization techniques, this study aims to develop a robust interconnection design. This design features a balanced configuration of TCT circuits that are electrically connected in parallel while being asymmetrically arranged. Building on the previous work (Siaw & Ooi, 2021), where the implications of layout configurations based on electrical connections, and the effect of shadowing some of the TCT segments were briefly discussed, this study expands on these topics. This work delves into explaining the system's power requirements, distinguishing between layout configurations and electrical connections, and assessing the effects of shadowing all TCT segments.

The remaining of the paper is organized as follows: Section 2 outlines the methodology used to determine the design capacity of the solar PV array under investigation, defines the array's layout configuration, and explains the setup of the simulation software and model. Section 3 presents the simulation results for the two random partial cloud shading scenarios and provides a discussion on why P-TCT outperforms SP and TCT. Finally, section 4 concludes with the findings of this study.

2. Methodology

2.1. Design Capacity

According to the Malaysia Energy Statistics Handbook 2021, the average electricity consumption per capita for Peninsula Malaysia in 2019 is 4,871 kWh (Malaysia Energy Statistics Handbook, 2021). The designed array features twenty-four solar modules, each with a capacity of 150 W. With an estimated daily operation of 4 hours, this configuration yields an annual total capacity of 5,256 kWh. This closely aligns with the electricity consumption per capita, which can also be considered as the energy needs of single occupant residences in Peninsular Malaysia.

2.2. Layout Configurations

In a series connection, the overall string's performance is impacted by the weakest module, rendering it more susceptible to shading effects. Conversely, in parallel connections, each module operates independently, mitigating the impact of shadowing (Sedeeq *et al.*, 2015). Nevertheless, parallel connections may introduce challenges related to voltage matching issues (Wurster & Schubert, 2014). To address the main challenges of series and parallel connections, total-cross-tied (TCT) can be implemented. Although TCT interconnections are known for challenging compatibility issues, TCT generally have high shading tolerance, higher efficiency and improved reliability (Mohammadnejad *et al.*, 2016; Pachauri *et al.*, 2021).

For a solar PV array, there are various possible array configurations of $m \times n$, where m is the number of rows of solar modules and n is the number of columns of solar modules. In addition, for each array configuration, there are multiple feasible electrical configurations of $p \times t$, where *p* is the number of TCT groups electrically connected in parallel and *t* is the number of solar modules in each TCT group. Furthermore, each TCT group can be further organized as $s \times l$, where *s* is the number of subsections in series, and *l* is the number of cells connected in parallel within each subsection. To simplify referencing, **Table 1** provides a summary of the configuration notations.

Table 1. Solar PV array matrix configuration notations

Configuration	Matrix	Description
Array	$m \times n$	*m* is the number of rows of solar modules *n* is the number of columns of solar modules
Electrical	$p \times t$	*p* is the number of TCT groups *t* is the number of solar modules in each TCT group
TCT	$s \times l$	*s* is the number of subsections in series *l* is the number of cells connected in parallel in each section

An array of twenty-four solar modules has eight possible array configurations, and also eight possible electrical configurations: 1 × 24, 2 × 12, 3 × 8, 4 × 6, 6 × 4, 8 × 3, 12 × 2, 1 × 24. The TCT configuration on the other hand is bound by the number of solar modules in each TCT group. For example, an array with an array configuration of 4 × 6 can have an electrical configuration of 3 × 8, and a TCT configuration of 4 × 2. The array configuration dictates the maximum output power of an array, while the electrical configuration determines the output current and voltage. In essence, an electrical configuration with more parallel-type branches generates higher currents at lower voltage, while an electrical configuration with more series-type branches generates lower currents at higher voltage. **Table 2** summarizes the available electrical configurations and their characteristics.

Based on the findings in **Table 2**, the possibility of grouping PV modules together was investigated. There are several approaches to configure the twenty-four PV modules into various TCT groups. To achieve maximum output power and for ease of study, all TCT groups must have the same number of PV modules and must be of the same symmetry. In this study, the twenty-four PV modules were arranged in a 4 × 6 array configuration which is suitable for most residential rooftops. For P-TCT interconnection design, aligning the objective of effectively mitigating partial shading conditions, the solar PV modules were configured electrically as 3 × 8, with 3 parallelly connected TCT groups. Each TCT group was further configured as an identical 4 × 2 arrangement, comprising four subsections in series, each with two modules. **Figure 1** illustrates the P-TCT interconnection design.

Table 2. Electrical configurations

p × *t* Configurations [a]	Characteristics
1 × 24 2 × 12 3 × 8	More susceptible to shading effect. Produces high current. Produces low voltage.
4 × 6 6 × 4	Moderately resilient to shading effect. Produces moderately high current. Produces moderately high voltage.
8 × 3 12 × 2 24 × 1	Less susceptible to shading effect. Produces low current. Produces high voltage.

[a.] *p* is the number of TCT groups, *t* is the number of modules in each TCT group

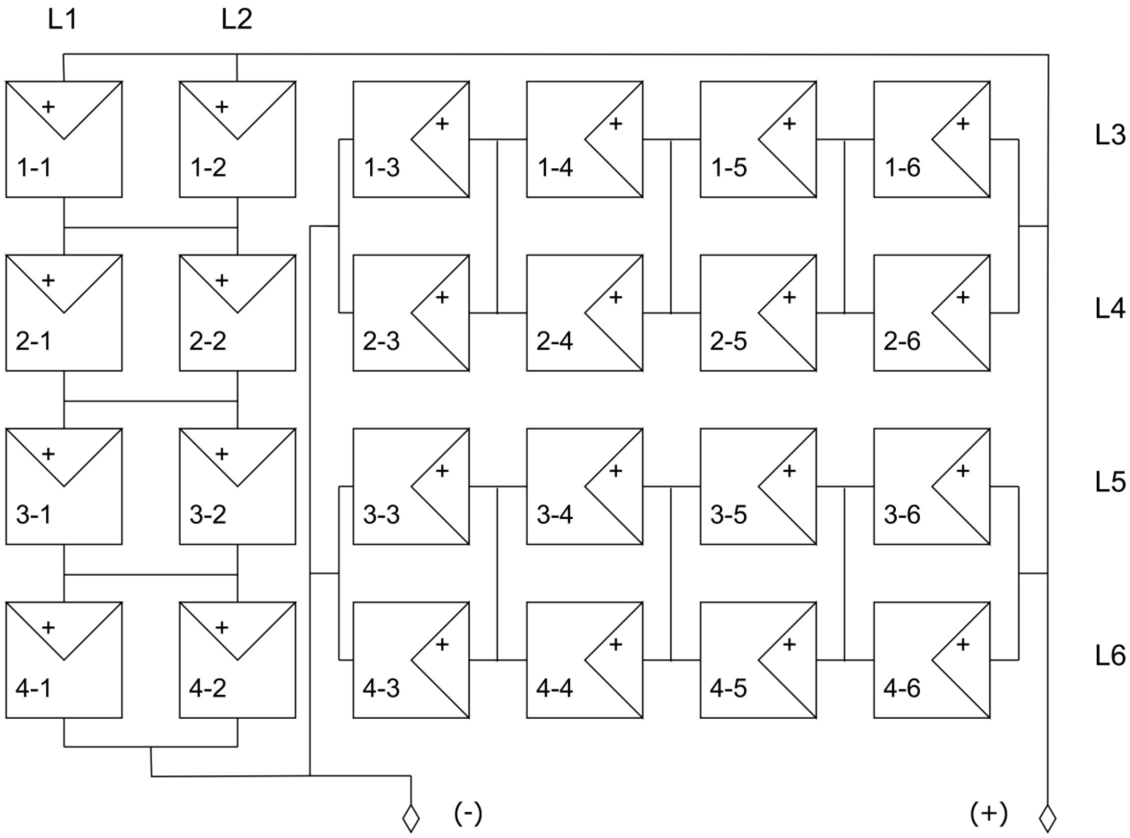


Figure 1. P-TCT design

As shown in **Figure 1**, one TCT group (branches L1 & L2) was aligned vertically, while two other TCT groups (branches L3 & L4, L5 & L6) were aligned horizontally. The reason for this is discussed in detail in the Results and Discussion subsections of Random Partial Cloud Shading Scenario 1 and Random Partial Cloud Shading Scenario 2. But in short, the argument is as follows: having TCT groups that are orthogonally aligned minimizes the risk of random partial cloud shading patterns that could block entire rows or columns of PV modules, which would significantly reduce power output.

2.3. Model Simulation

MATLAB Simulink was used for modelling the effects of irradiance and temperature on the PV array. The simulation model was separated into two parts, namely the main system and the subsystem.

The subsystem, as illustrated in **Figure 2**, houses the twenty-four interconnected PV modules which form the PV array. The twenty-four PV modules in the subsystem was configured based on the layout configurations being tested, which are SP, TCT and our proposed P-TCT. The PV modules were rated at 150 W.

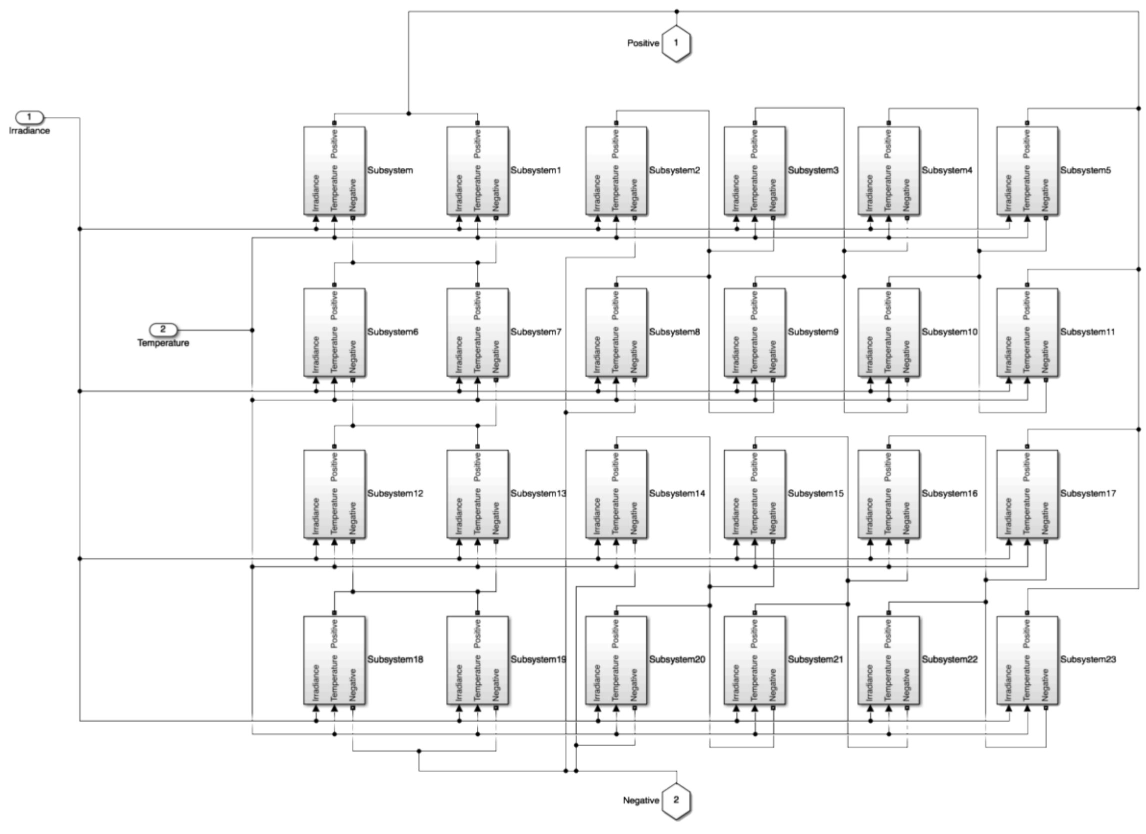


Figure 2. Subsystem of P-TCT design in MATLAB Simulink

The main system, as depicted in **Figure 3** fed the uniform irradiance, temperature and nonuniform irradiance inputs to the subsystem, and performed measurement of output current, voltage, and power. The measurement was performed using both Simulink and Simscape modules, including a controlled voltage source, a voltage measurement module, a current measurement module, an IV graph plotter, and a PV graph plotter.

To replicate real world partial cloud shading scenarios, the uniform irradiance was maintained at 1,000 W/m^2 while the nonuniform irradiance was systematically varied from 0 to 999 W/m^2. As this study only concentrated on the effect of partial cloud shading, the input temperature was held constant at 25˚C. The performance of the three designs: SP, TCT, and our novel P-TCT was then assessed to determine the effectiveness of the layout for mitigating mismatch loses in non-uniform irradiation conditions. The interconnections of the three configurations can be observed in **Figure 4** and **Figure 5**.

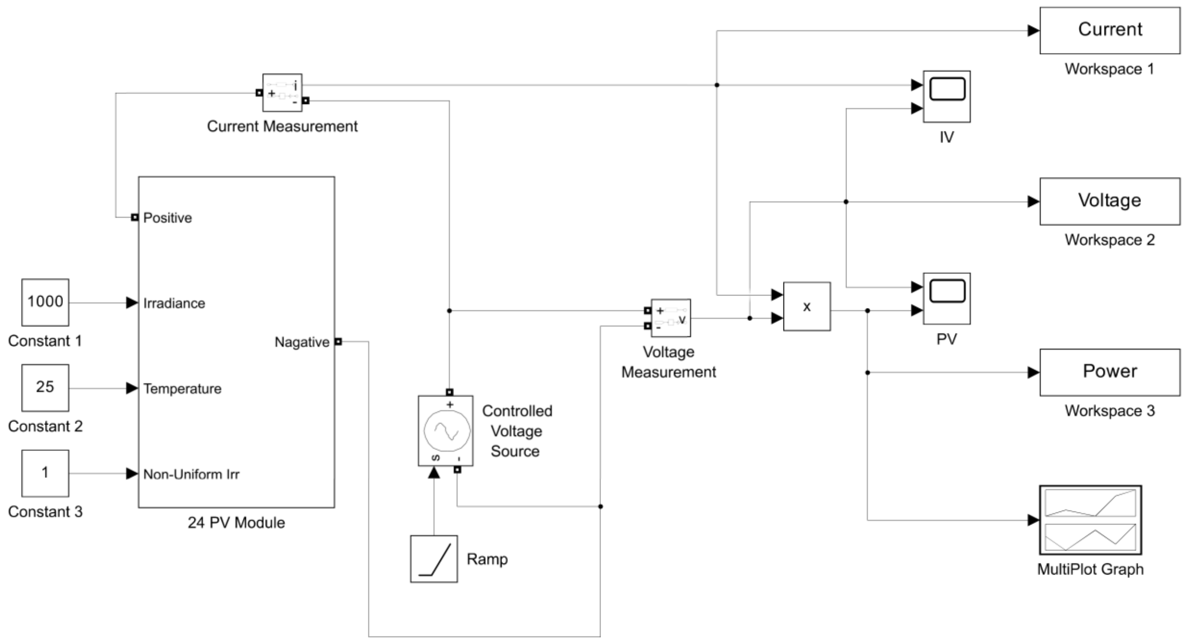


Figure 3. Main system of design in MATLAB Simulink

3. Results and Discussion

The objective of a well-designed PV array configuration is to maximize power output by mitigating the impact of partial cloud shading on the PV array. Under ideal conditions, the 4 × 6 PV array had a simulated maximum power of 3,594 W, with a maximum output current I_{mp} of 48.56 A and a maximum output voltage V_{mp} of 74 V. To evaluate the resiliency of the

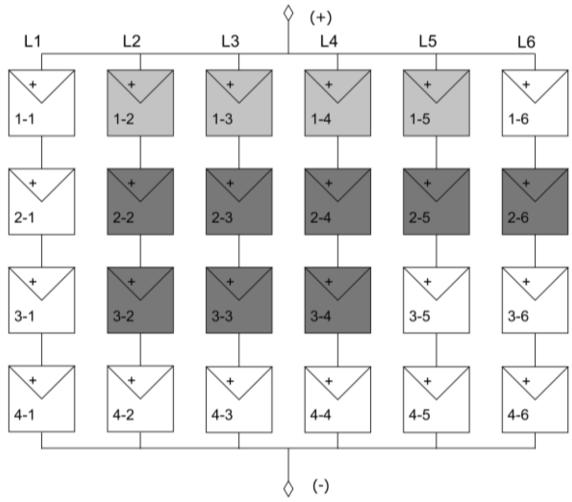
SP, TCT and P-TCT designs under partial cloud shading conditions, further simulations were then conducted using two random partial cloud shading patterns. To mimic actual shading from translucent cloud formations, different shading intensities were applied. For illustration, the two random partial cloud shading patterns tested are shown in **Figure 4** and **Figure 5**, where the simplified models of all three competing layouts are overlaid with varying shades of grey to indicate the different levels of shading. Darker grey represents higher shading with lower irradiance, while lighter grey indicates less shading with higher irradiance.

3.1. Random Partial Cloud Shading Scenario 1

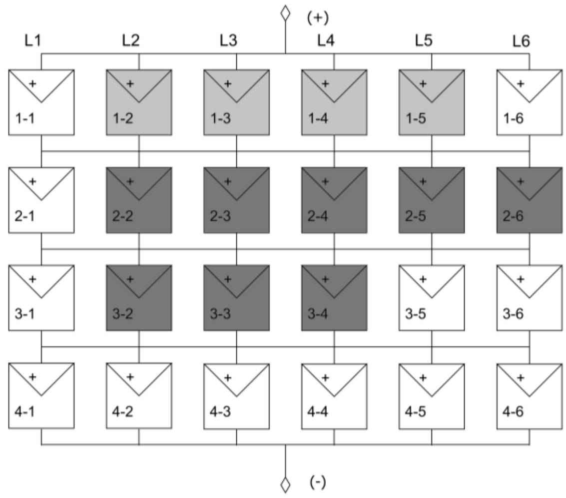
The first random partial cloud shading pattern concentrated on the upper and central regions of the twenty-four-module PV array. **Figure 4** provides a visual presentation of the simplified simulation models for all three interconnections, with varying levels of shading depicted by the different shades of grey. As depicted in **Figure 4**, in the top row, four PV modules, specifically modules 1-2, 1-3, 1-4, and 1-5 were exposed to a moderate degree of shading, with input irradiance values set to 500 W/m^2. In contrast, within the central region of the twenty-four-module PV array, a larger group of eight PV modules, specifically modules 2-2, 2-3, 2-4, 2-5, 2-6, 3-2, 3-3, and 3-4 were exposed to a higher degree of shading, and the input irradiance value was reduced to only 300 W/m^2. The results gathered are then tabulated in **Table 3**.

As shown in **Table 3**, the proposed P-TCT design had demonstrated superior performance under random partial cloud shading scenario 1, achieving the highest power generation of 2,145 W. In contrast, both SP and TCT designs yielded significantly lower power outputs of 1,568 W and 1,687 W respectively. This variation in output suggests that both SP and TCT configurations are less effective in mitigating mismatch losses.

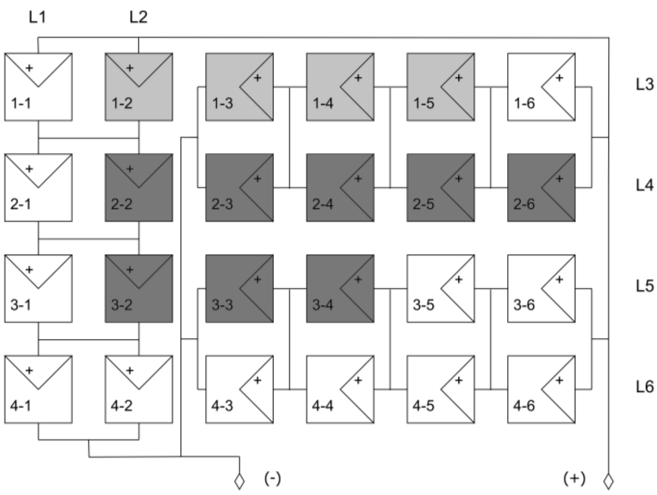
In the case of the SP design (**Figure 4**), it is evident that parallel branches L2, L3, L4, L5, and L6 became almost inactive due to high shading affecting the central modules, specifically modules 2-2, 2-3, 2-4, 2-5, 2-6, 3-2, 3-3, and 3-4. Consequently, only parallel branch L1 remained fully operational. Upon closer examination of the TCT design, it became apparent that current pathways within branches L2, L3, L4, L5, and L6 were severely constrained by shading. However, the TCT configuration demonstrated marginally better performance, as it allowed for some of the currents from the active modules of these branches to be redirected to the fully operational branch L1.



(a) Serial Parallel (SP)



(b) Total-Cross-Tied (TCT)



(c) Parallel Connected Total-Cross-Tied (P-TCT)

Figure 4. Random partial cloud shading scenario 1 for (a) SP, (b) TCT and (c) P-TCT

Table 3. Results for random partial cloud shading scenario 1

Interconnection	Current, I (A)	Voltage, V (V)	Power, P (W)
SP	20.41	76.8	1,568
TCT	21.19	79.6	1,687
P-TCT	28.07	76.4	2,145

In the P-TCT design (**Figure 4**), all the modules in branch L4 were inactive due to heavy shading, and in branches L2 and L5, current pathways were significantly restricted due to heavy shading of modules 2-2 and 3-2 in branch L2, and modules 3-3 and 3-4 in branch L5. However, thanks to the TCT interconnection pairs of branches L1 with L2, and of branches L5 with L6, current flow from the remaining active modules from branch L2 and branch L5 were respectively redirected through branch L1 and branch L5, partly mitigating the shading effects. Additionally, partially active PV modules in branch L3 made a modest contribution to the overall power generation of the P-TCT design. To summarize, the P-TCT design yielded an overall power output that surpasses the SP and TCT designs by 36.8% and 27.1%, respectively. This result aligns with previous research, where similar TCT-based improved designs demonstrated enhancements of 41.62% over SP and improvements ranging from 27.9% to 88.57% over TCT designs (Pachauri *et al.*, 2021; Pareek *et al.*, 2017).

3.2. Random Partial Cloud Shading Scenario 2

In contrast to random partial cloud shading scenario 1, random partial cloud shading scenario 2 focused on the left and bottom regions of the twenty-four-module array. **Figure 5** visually illustrates the simplified simulation models for all three interconnections, where varying degrees of shading is represented by the different shades of grey. As depicted in **Figure 5**, on the left region, six PV modules, specifically modules 1-1, 1-2, 2-1, 2-2, 3-1, and 3-2 were exposed to a low degree of shading, with input irradiance values set to 700 W/m^2. In contract, at the bottom region of the twenty-four-module PV array, five PV modules, specifically modules 4-1, 4-2, 4-3, 4-4, and 4-5 were exposed to a higher level of shading, and the input irradiance value was reduced to only 300 W/m^2. The results gathered are then tabulated in **Table 4**.

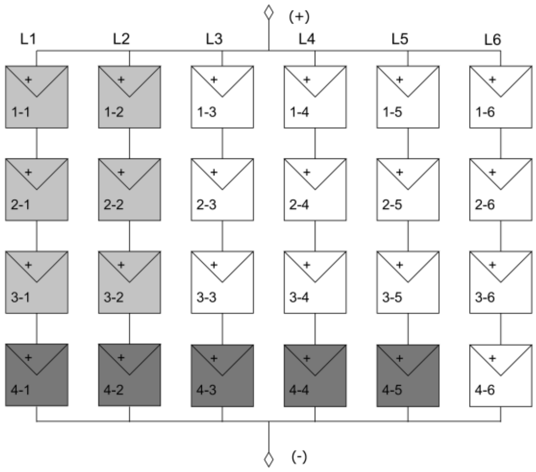
Table 4. Results for random partial cloud shading scenario 2

Interconnection	Current, I (A)	Voltage, V (V)	Power, P (W)
SP	16.57	78.0	1,293
TCT	16.98	81.4	1,383
P-TCT	29.36	74.8	2,197

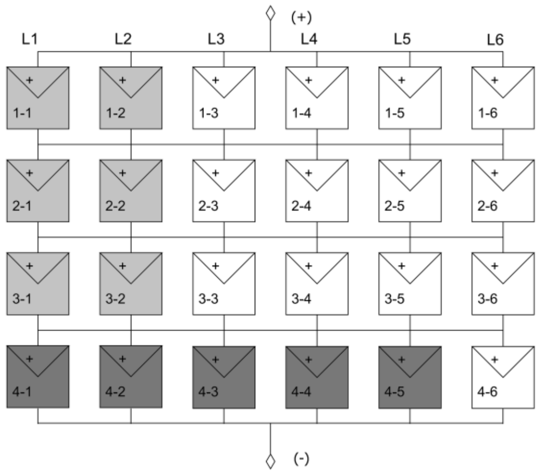
Table 4 shows that under random partial cloud shading scenario 2, the proposed P-TCT design had again delivered the highest power generation of 2,197 W. In comparison, SP and TCT configurations only managed to deliver low power outputs of 1,293 W and 1,383 W respectively. This variation in output suggests that the P-TCT design is superior to both SP and TCT configurations when it comes to mitigating mismatch losses.

In the case of the SP design (**Figure 5**), it is evident that parallel branches L1, L2, L3, L4, and L5 were only able to deliver very little power due to heavy shading of the bottom modules, specifically modules 4-1, 4-2, 4-3, 4-4, and 4-5. Consequently, only parallel branch L6 remained fully operational. As for the TCT design, it became apparent that current pathways within branches L1, L2, L3, L4 and L5 were severely constrained by shading of modules 4-1, 4-2, 4-3, 4-4, and 4-5. However, like the case of random partial cloud shading scenario 1, the TCT configuration allowed for some of the currents from the active modules of these branches to be redirected to branch L6, thus giving it marginally better performance.

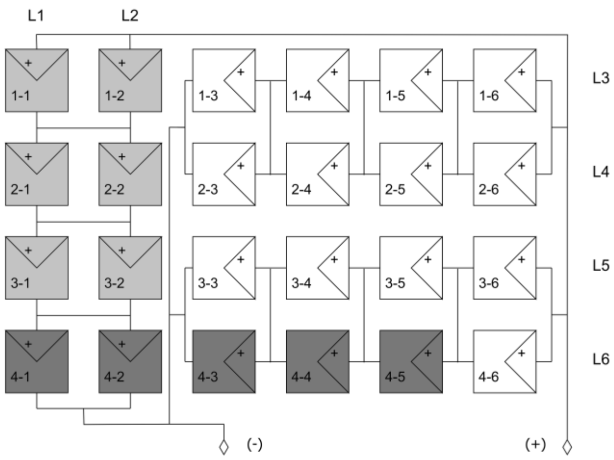
In the P-TCT design (**Figure 5**), the branches of L1, L2 and L6 were producing very limited power output because the heavily shaded bottom modules of 4-1, 4-2, 4-3, 4-4, and 4-5 were operating at minimal capacity. However, because branches L6 and L5 were interconnected as a TCT pair, current flow from the remaining active modules from branch L6 was redirected through branch L5. This, in combination to the TCT pair of branches L3 with L4 operating at full capacity, contributed to the overall increased power generation output of the P-TCT design. In summary, the P-TCT design yielded a remarkable 69.9% and 58.8% higher power output compared to the SP and TCT designs, respectively. While the performance improvement over SP surpasses that of previous research, which demonstrated enhancements of 41.62% over SP for similar TCT-based improved design, the performance improvement over the TCT designs aligns with results from prior research, showing improvements ranging from 27.9% to 88.57% (Pachauri *et al.*, 2021; Pareek *et al.*, 2017). However, it is important to note that a direct comparison may not be feasible due to differences in layout configuration, the number of PV modules, and the random shape of the partial shading.



(a) Serial Parallel (SP)



(b) Total-Cross-Tied (TCT)



(c) Parallel Connected Total-Cross-Tied (P-TCT)

Figure 5. Random partial cloud shading scenario 2 for (a) SP, (b) TCT and (c) P-TCT

4. Conclusion

In solar PV systems, one of the most prevalent challenges is partial cloud shading, which significantly reduces power generation due to mismatch issues. This study presents an optimized P-TCT design that incorporates the splitting technique to effectively mitigate partial cloud shading effects. The optimized design is demonstrated with twenty-four PV modules organized in a 4 × 6 configuration. These modules were divided into three TCT groups, each with four subsections in series and each subsection having two modules. This innovative interconnection minimizes mismatch losses, leading to an overall increased in power output. To evaluate the effectiveness of the P-TCT design, it was rigorously tested and compared to conventional SP and TCT configurations using MATLAB simulation models. Under ideal shadeless condition, the proposed design achieved a P_{mp} of approximately 3,594 W. Subsequently, various simulated scenarios encompassing random partial cloud cover and varying irradiance values were executed. The simulations show that among the three configurations, the P-TCT consistently outperformed the SP and TCT alternatives, showcasing enhancements of up to 69.9% and 58.8% in power output. These results highlight the P-TCT design as the optimal choice, effectively mitigating mismatch losses and surpassing the performance of SP and TCT configurations.

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Credit Author Statement

Conceptualization and methodology, Thio, T.H.G., Siaw, F. L., and Faisal T.; software and validation, Ooi, Y.Z., formal analysis, Thio, T.H.G; investigation, Ooi, Y.Z.,; resources, Siaw, F.L.; data curation, Thio, T.H.G. and Siaw, F.L.; writing—original draft preparation, Thio, T.H.G., Siaw, F.L., Faisal T. and Ooi, Y.Z.; writing—review and editing, Thio, T.H.G,; visualization, Thio, T.H.G,; supervision and project administration, Siaw, F.L.

Conflicts of Interest

The authors declare no conflict of interest.

References

Alahmad, M., Chaaban, M. A., Lau, S. k., Shi, J., & Neal, J. (2012). An adaptive utility interactive photovoltaic system based on a flexible switch matrix to optimize performance in real-time. *Solar Energy,* 86(3), 951-963.

Albadi, M.H. (2019). Solar PV power intermittency and its impacts on power systems - an overview. *Journal of Engineering Research,* 16(2), 142-150.

Ali, S., El Iysaouy, L., Lahbabi, M., Boujoudar, Y., Alharbi, S. J., Azeroual, M., Bassine, F. Z., Aljarbouh , A., Knyazkov, A., Albarakati, A., Rele, & M., Ness, S. (2023). A matlab-based modelling to study and enhance the performance of photovoltaic panel configurations during partial shading conditions. *Frontiers in Energy Research,* 11.

Bassi, H., Salam, Z., Ramli, M. Z., Sindi, H., & Rawa, M. (2019). Hardware approach to mitigate the effects of module mismatch in a grid-connected photovoltaic system: A review. *Energies,* 12(22), 4321.

Das, S. K., Verma, D., Nema, S., & Nema, R. K. (2017). Shading mitigation techniques: State-of-the-art in photovoltaic applications. *Renewable and Sustainable Energy Reviews,* 78, 369-390.

El-Dein, M. Z. S., Kazerani, M., & Salama, M. M. A. (2012). An optimal total cross tied interconnection for reducing mismatch losses in photovoltaic arrays. *IEEE Transactions on Sustainable Energy,* 4(1), 99-107.

Kurmanbay, A., Baktybekov, K., Sakhanov, K., Syzdykov, A., & Mukhamediyev, A. (2020). Optimization of series-parallel connection of PV array to mitigate negative influence of partial shading conditions. *IOP Conference Series: Materials Science and Engineering,* 868(1), 012001, IOP Publishing.

Malaysia Energy Statistics Handbook. (2021). *Department of Energy Management and Industrial Development Suruhanjaya Tenaga (Energy Commission).*

Mohammadnejad, S., Khalafi, A., & Ahmadi, S. M. (2016). Mathematical analysis of total-cross-tied photovoltaic array under partial shading condition and its comparison with other configurations. *Solar Energy,* 133, 501-511.

Narne, D. K., Ramesh Kumar, T. A., & Alla, R. (2023). Evaluation of series-parallel-cross-tied PV array configuration performance with maximum power point tracking techniques under partial shading conditions. *Clean Energy,* 7(3), 620-634.

Niazi, K. A. K., Yang, Y., & Sera, D. (2019). Review of Mismatch Mitigation Techniques for Photovoltaic Modules. *IET Renewable Power Generation,* 13(12), 2035-2050.

Owusu, P. A., & Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering,* 3(1), 1167990.

Pachauri, R. K., Bai, J., Kansal, I., Mahela, O. P., & Khan, B. (2021). Shade dispersion methodologies for performance improvement of classical total cross-tied photovoltaic array configuration under partial shading conditions. *IET Renewable Power Generation,* 15(8), 1796-1811.

Pareek, S., Chaturvedi, N., & Dahiya, R. (2017). Optimal interconnections to address partial shading losses in solar photovoltaic arrays. *Solar Energy,* 155, 537-551.

Sedeeq, S. Z., Ameen, A. H., & Muhammadsharif, F. F. (2015). Effect of series and parallel shading on the photovoltaic performance of silicon based solar panels. *Journal of Technology Innovations in Renewable Energy,* 4, 152-156.

Sher, F., Curnick, O., & Azizan, M. T. (2021). Sustainable conversion of renewable energy sources. *Sustainability,* 13(5), 2940.

Siaw, F. L., & Ooi, Y. Z. (2021). Photovoltaic array interconnection optimization based on cloud cover. *Advances in Material Science and Engineering,* Springer, Singapore.

Soomar, A. M., Hakeem, A., Messaoudi, M., Musznicki, P., Iqbal, A., & Czapp, S. (2022). Solar photovoltaic energy optimization and challenges. *Frontiers in Energy Research,* 10, 879985.

Wurster, T. S., & Schubert, M. B. (2014). Mismatch loss in photovoltaic systems. *Solar Energy,* 105, 505-511.

Yang, Y., & Siaw, F. L. (2021). An improved variable step size MPPT method for photovoltaic array under partial shading conditions. *Journal of Engineering and Technological Advances*, 6(1), 1-16.

Yin, J., Molini, A., & Porporato, A. (2020). Impacts of solar intermittency on future photovoltaic reliability. *Nature Communications,* 11(1), 4781.