Mitigating Partial Shading Effects in Photovoltaic System using Intelligent Current Compensation Method

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Abstract. Efficiency of photovoltaic (PV) systems is decreased by mismatch losses resulting from uneven panel irradiation. Current compensation techniques that inject compensatory current and measure currents by periodic row short-circuiting are unavoidably blackout-causing. In this work, a novel current compensation technique is presented that dynamically measures and reacts to variations in irradiance using light sensors on each panel. The program compiles these data to determine the overall irradiance of each row and to precisely modify the injected current to sustain output without any interruptions to operation. The proposed approach lowers mismatch losses more effectively than traditional techniques, as demonstrated by MATLAB/Simulink simulations of seven shading patterns. Under center shading, the proposed approach raised system efficiency by 36%. These results indicate a move towards more flexible solar energy solutions by implying that sensor-driven data analytics can increase PV system operational efficiency and reliability.

1 Introduction

Renewable energy innovations solve carbon emissions and fossil fuel depletion [1], [2], [3]. Development usually favors renewable energy sources with simple harvesting and low harvesting costs. Solar energy conversion (SEC) has fewer drawbacks than direct implementation and rural electrification. SEC systems collect it using photovoltaics and solar thermal conversion. Solar photovoltaic conversion is an efficient and environmentally friendly way to electrify rural areas. Solar PV systems convert sunlight into electrons using the photovoltaic effect [4]. Commercial applications included polycrystalline, monocrystalline, thin-film, bifacial, and photovoltaic buildings [5].

PV cells are arrayed by power need. Array topologies are classified as series-parallel or module interaction. Mismatch losses are the biggest concern in array construction. This mismatch loss is caused by PV module power generation differences. Photovoltaic (PV) systems also suffer from partial shade, hotspot, delamination, degradation, diode failure, string burning, and isolated PV cells or modules that cause mismatch losses across PV array rows [6], [7], [8]. PV modules and row creation generate electricity, which affects PV array power output. Due to these factors, some rows generate the rated power and others less. The power difference between healthy and defective PV rows is called MLs. When PV is integrated into the grid, it affects grid stability until the PV generates the expected power [9]. To reduce mismatch losses, MPPT, array configuration, PV array reconfiguration, and current compensation are being investigated. Previous MPPT versions used perturb and observation. Later, incremental conductance MPPT methods were developed. However, partially shaded photovoltaic (PV) systems produce power (P)-voltage (V) and current (I)-voltage (V) curves that are not smooth [10], [11]. A non-smooth curve may have many local maximum power points. There are many maximum power points, making it hard to determine the Global Maximum Power Point (GMPP). The majority of MPPT algorithms produce inefficient GMPPs. MPPT optimizes and uses soft computing to improve performance. MPPT is used in fuzzy logic control, neural networks, AI, ant colony optimization, particle Swarm optimization, and more. [12]. Tracking the MPPT fails to track the GMPP in difficult situations. The MPPT cannot distribute shade throughout the PV array, another drawback. Besides mismatch loss reduction, PV array reconfiguration is an option[6], [13], [14]. This uses dynamic switching circuits to change PV module interconnections to spread faults across an array [15]. This technology is expensive because it uses sensors, switches, and other controls [16], [17]. External power compensation sources are connected to each panel or row simultaneously to compensate for power loss [18]. Thus, array mismatch

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losses are eliminated. Construction and maintenance of this compensation method are costly.

Power demand with required specifications is usually generated using array configuration. Partial shadowing depends on array structure. Series, Parallel, and Series-Parallel array configurations are common in PV applications [19], [20]. However, these arrays cannot disperse partial shade effects. Power output increases when photovoltaic modules are dynamically connected. The initial goal of the total cross-tied (TCT) system was to connect each panel in parallel and series with nearby PV modules. These conditions reduce the shaded panel effect in series connections. PV row mismatch loss occurs when a row is completely blocked. This reduces power generation. Competent square, dominating square, skyscraper, magic square pattern-based, Sudoku, Futoshiki, honey-comb, bridge-linked, and other array configurations can be used to reduce mismatch losses in advanced TCT [21]. Each array configuration uses different logic. Logics may have mathematical formulations with constraints. Honeycombs inspired the honeycomb-shaped PV string connections. In a bridge-linked array, photovoltaic strings are connected by bridges. Sudoku and Futoshiki are used to build the PV array [22, 23]. Magic square arrays have equal row, column, and diagonal sums. After minor adjustments, the magic square array is followed by competent and dominant squares [23], [24], [25]. L-shaped propagation array row structure was inspired by chess knight coin movement [26]. Along with building the nodes, the spiral pattern array was created [27]. These array setup combinations are the most common and current. System mismatch loss can be greatly reduced with new logic. The configurations are better in some known environmental conditions, but they failed to disperse loss-causing factors in some worst cases. Incorporating new logics with efficient operation in all configurations improves PV power generation. This method addresses these challenges and proposes a new solution for the reduction of mismatch losses. The contribution of this proposed work are,

- Real-Time Irradiance Measurement: A new technique was presented to dynamically modify current injection, guaranteeing uniform current distribution and lowering mismatch losses, by using real-time irradiance measurements from light sensors on each PV panel.
- Improved Performance Under Shading: Using MATLAB/Simulink simulations, showed notable increases in power output and system efficiency across different shading patterns, outperforming traditional Total Cross-Tied (TCT) configurations.
- Short-circuiting rows is not necessary for the proposed technique to operate continuously, which eliminates blackout periods and guarantees a steady power supply.
- Reliability of PV systems is increased by the simplicity of the system setup and the reduction of possible points of failure brought about by the removal of switches and current sensors.

2 Proposed Method

Photovoltaic (PV) systems experiences power loss for a number of reasons. Efficiency is greatly reduced by partial shading, in which structures or trees obscure sunlight on portions of the PV array. Dirt and debris building up on the panel surfaces causes soiling, which reduces light absorption and total power output. Variations in temperature are also quite important; high temperatures can reduce module efficiency and raise system resistance. Variations in module performance, frequently brought on by aging, uneven irradiation, or manufacturing variations, cause mismatch losses. Power dissipation also results from electrical resistance in connections and wires. Long-term environmental exposure degradation reduces PV cell efficiency even more. PV system performance optimization depends on addressing these problems with efficient mitigation techniques.

The Fig. 1 illustrate the significant impact of varying irradiance levels on the electrical characteristics of photovoltaic (PV) modules. The short circuit current (Isc) rises in tandem with irradiance. This proves that the PV modules produce more current at higher irradiance levels. With changing irradiance, the open-circuit voltage (Voc) varies comparatively little from the current. While it rises somewhat with increasing irradiance, the voltage is less sensitive to variations in light intensity than the current. One Maximum Power Point (MPP) on the power-voltage curve is associated with each irradiance level. Higher MPPs indicate that the PV module generates more power in higher irradiance levels of sunshine. A PV module's power output rises dramatically with increasing irradiance levels. This emphasizes the need of optimizing light exposure to increase PV systems' energy yield.

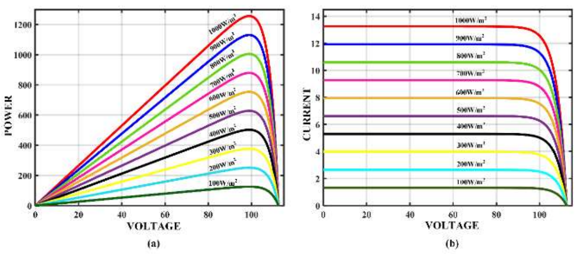

Fig. 1. Performance of a PV system with respect to the solar irradiance

In photovoltaic (PV) systems, mismatch losses result from unequal irradiation of PV panels and greatly lower system efficiency overall. In order to solve this problem, we present a new current injection technique that dynamically modifies the current across the PV array by using real-time solar irradiance data. This approach tries to increase efficiency and dependability by guaranteeing constant current distribution across all rows without operational blackouts. Fig. 2 shows the flow charts of the conventional and proposed current compensation methods.

2.1 Conventional Current Injection Method

In the traditional approach, current mismatches are measured and corrected for by a sequence of steps

- Measure Load Current (I_L): The state of the system is first ascertained by measuring the load current.
- Wait for 5 Seconds: The present measurement is stabilized by a little holding period.
- Measure Load Current Again (I_{Lnew}): Following the waiting time, the load current is taken once again.
- Calculate Current Difference (ΔIL): The initial and new load current differences are determined:

$$\Delta I_L = I_L - I_{L,new}$$

- Check if $(\Delta I_L \geq 5\%)$: Verify if a big mismatch is indicated by a difference more than 5%.
- Short-Circuit All Rows (IR): The row currents are measured by short-circuiting every row (IR).
- Determine Injection Current (Iinj): This determines how much injection current each row needs:

$$I_{inj} = I_{STC} - I_R$$

Where I_{STC} the present of the standard test condition is.

- Inject I_{inj} to Each Row: To offset the mismatch, the calculated injection current is injected into each row.
- Wait for Operating Period: Prior to the subsequent measurement cycle, the system holds for a predetermined operating period.
- Remove Injection Current: The system restarts normally after the injection current is removed.

Among the many disadvantages of this approach are blackout times during short-circuit measurements, more switches and current sensors in the system, and a delayed reaction to changing irradiance conditions.

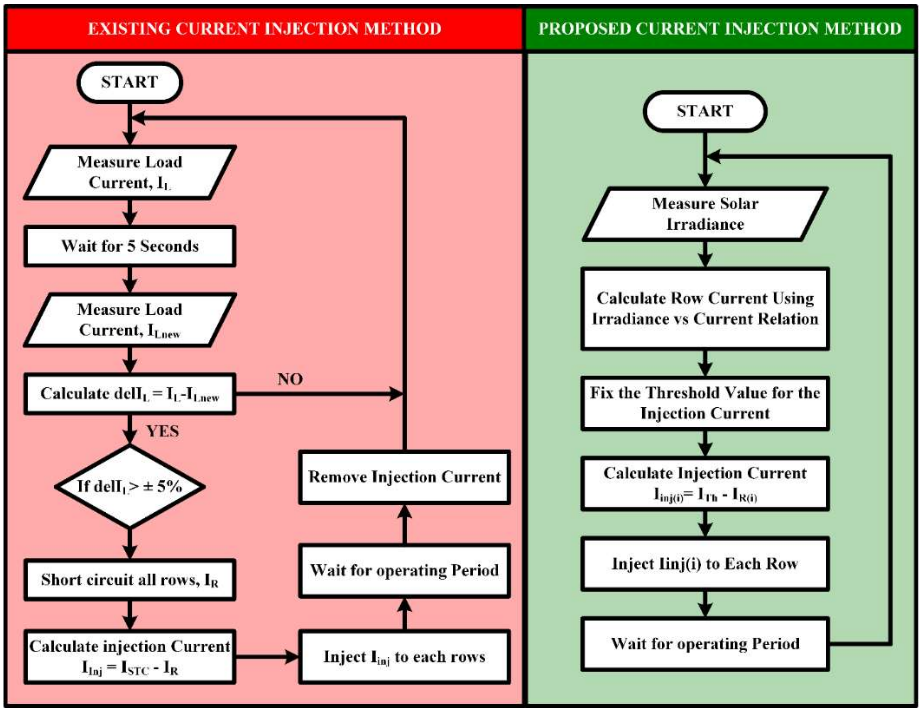

Fig. 2. Flow chart of the proposed and conventional method

2.2 Proposed Current Injection Method

The proposed method offers a more efficient and reliable approach by leveraging real-time irradiance measurements:

- Start: The process begins with system initialization.
- Measure Solar Irradiance: A light-dependent resistor (LDR) or other comparable light sensor is included into every PV panel to measure solar irradiance continuously.
- Calculate Row Current Using Irradiance vs. Current Relation: The algorithm adds the irradiance values of every panel in a row to determine the anticipated row current based on measured irradiance:

$$I_{row} = \sum_{i=1}^{n} I_{panel_i} \times \frac{G_{actual}}{G_{STC}}$$

- Fix the Threshold Value for the Injection Current: The least deviation that initiates current compensation is determined by setting a threshold value.: $\Delta I_{threshold}$
- Calculate Injection Current: Every row's injection current is determined by subtracting the measured row current from the ideal row current (which is obtained from the row with the highest irradiance):

$$I_{inj}(t) = I_{max} - I_{row}(t)$$

- Inject $I_{inj}(t)$ to Each Row: Dynamically injecting the computed injection current into each underperforming row equalizes the current across all rows.
- Wait for Operating Period: To allow stabilization, the system waits for a predetermined operating period before the next cycle of measurement and adjustment.

2.3 Comparison of the Methods

The traditional technique causes blackout periods when no electricity is produced by periodically short-circuiting PV rows and current measurements. Furthermore adding to the complexity and possible failure points are switches and current sensors. Its efficacy is further diminished by the delayed reaction to shifting irradiance conditions. Using real-time irradiance measurements from light sensors, on the other hand, the proposed approach eliminates blackout periods and simplifies setup by doing away with switches and current sensors. Because it calculates and injects current instantly using real-time data, it guarantees quick and ongoing adaptation to changing irradiance conditions. Mismatch loss mitigation is much improved by this dynamic and continuous current adjustment, which raises PV system efficiency and dependability. By using sensor-driven data analytics to sustain uniform current distribution and maximize power output under different shading conditions, the proposed current injection method provides a significant improvement over conventional approaches.

3 Simulation Analysis

The proposed method has been modelled and validated in MATLAB/Simulink. Simulations are performed in several shading patterns—corner, center, frame, Short Narrow (SN), Short Wide (SW), Long Narrow (LN), and Long Wide (LW)—were used to evaluate the proposed current compensation method as shown in Fig. 3.

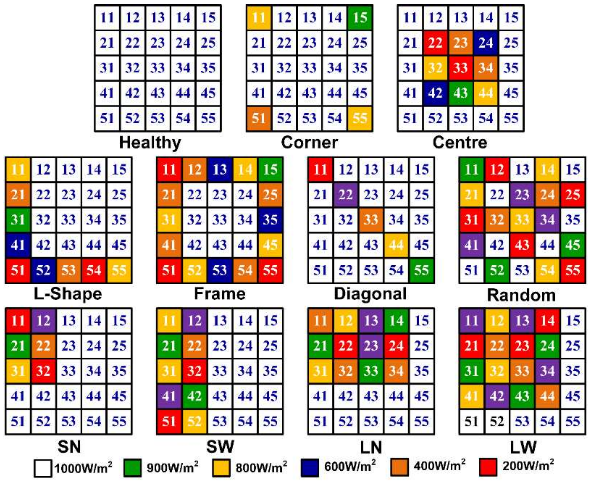

Fig. 4. Different Kinds of Shading Pattern

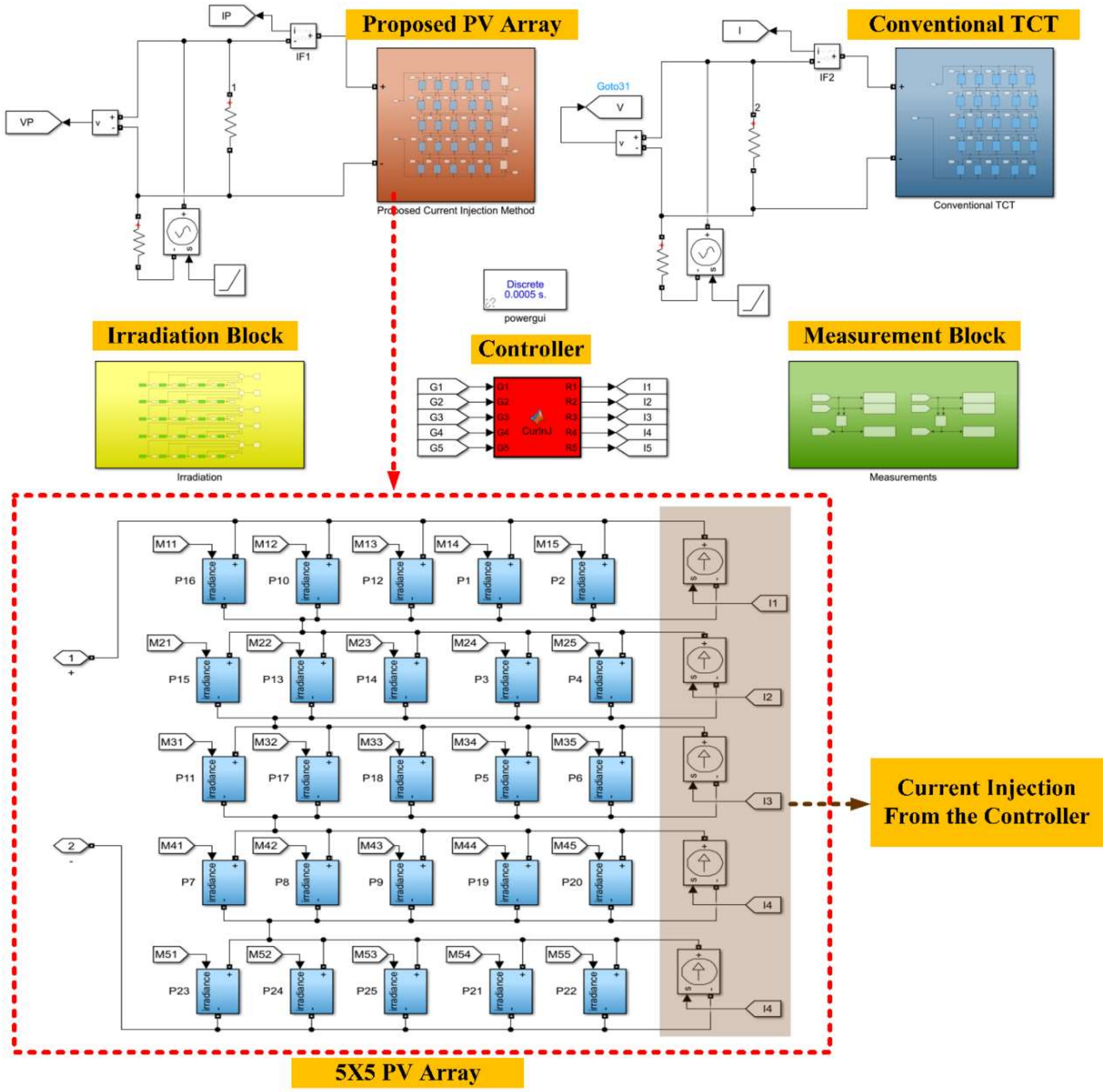

Fig. 4. Simulation of the Proposed method in MATLAB/Simulink

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The MATLAB/Simulink model has shown in Fig. 4. Key performance metrics including maximum current, maximum power, and overall system efficiency were the main focus of the comparison between the proposed approach and the traditional Total Cross-Tied (TCT) configuration. The simulations show that the proposed technique greatly improves PV system performance in various shading situations. In corner shading, for example, the proposed approach demonstrated a significant increase in current injection, so lowering mismatch losses and enhancing overall performance. In other shading situations as well, this pattern remained constant.

Regarding center shading, which with traditional techniques usually causes significant mismatch losses, the proposed approach successfully made up for these losses while preserving a more steady power output. This shows that the proposed technique can manage very dark situations where traditional techniques fail. The characteristic curves under corner shading is shown in Fig. 5. The proposed approach once more outperformed the conventional method under frame shading conditions, exhibiting a higher maximum power output. The characteristic curves under center shading and frame shading are shown in Fig. 6 and Fig. 7. This shows that it works well to lessen the negative impacts of partial shading, which is essential to preserving peak performance in practical PV installations. Varying irradiance levels are produced throughout the PV array by the SN shading pattern. Under these circumstances, the real-time adjusting features of the proposed approach greatly improved system performance. In a similar vein, the proposed approach was able to sustain greater efficiency and power output than the traditional TCT method under SW shading. The characteristic curves under SN shading and SW shading are shown in Fig. 8 and Fig. 9. The proposed technique efficiently managed the LN shading pattern, which in conventional systems results in large power losses. It also guaranteed uniform current distribution. The characteristic curves under LN shading and LW shading are shown in Fig. 10 and Fig. 11.. Similar to this, the proposed technique successfully reduced the LW shading pattern, which usually causes significant power losses, improving overall performance. Real-time adjustments made by the proposed approach emphasize its efficacy even more. The proposed approach guarantees best performance even in fast changing environmental conditions by dynamically modifying the current injection and continuously monitoring irradiance levels. Compared to traditional techniques, which depend on sporadic measurements and adjustments, resulting in delayed responses and lower efficiency, this real-time response ability is a major advance. The required injection current was measured in each case was measured by the controller, and the injection current on each shading cases are given in table 1. Similarly, the performance of the proposed method over the conventional method has been validated and compared. This comparison result has been given in table 2.

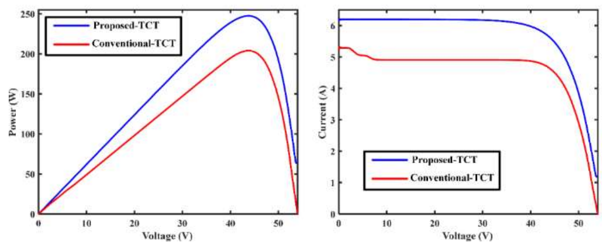

Fig. 9. Performance curves under SW Shading

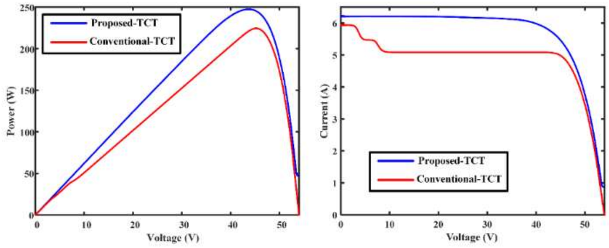

Fig. 5. Performance curves under Corner Shading

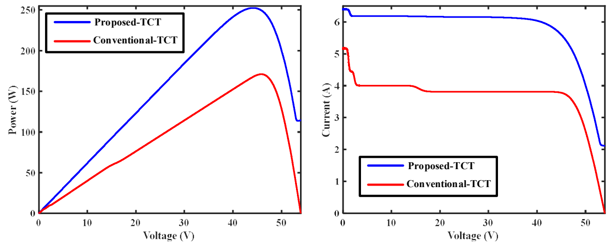

Fig. 6. Performance curves under Center Shading

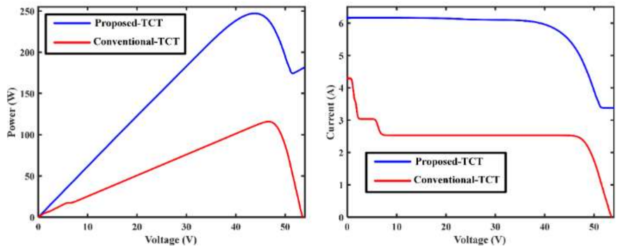

Fig. 7. Performance curves under frame shading

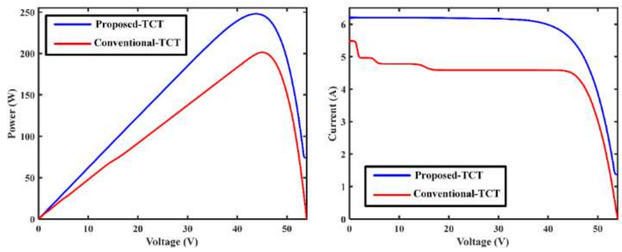

Fig. 8. Performance curves under SN Shading

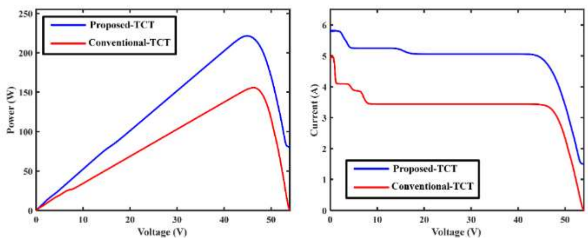

Fig. 10. Performance curves under LN Shading

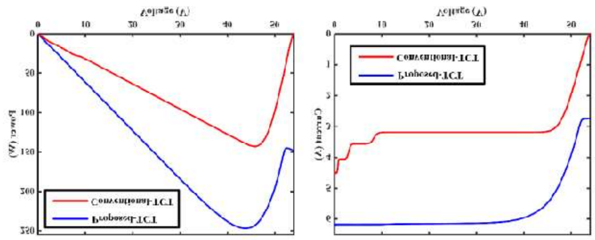

Fig. 10. Performance curves under LW Shading

A major benefit of the proposed approach is the removal of blackout periods. The proposed approach runs continuously and without interruption, unlike traditional methods that need short-circuiting rows and so experience periods of no electricity production. Consistent energy output depends on a steady power supply, which this continuous operation guarantees in addition to increasing overall efficiency. The results show that, for all tested shading patterns, the proposed current compensation technique routinely outperforms the traditional TCT configuration in terms of power output and efficiency. This shows the robustness and flexibility of the proposed approach to different shading situations, which are typical in actual PV installations.
The design of PV systems will be greatly impacted. Several practical benefits of the proposed current compensation technique include higher efficiency, higher reliability, and increased power output. Even in the presence of some shading, PV systems can maintain higher efficiency and power output by combining dynamic current adjustments with real-time irradiance measurements.

Table 1. Injection Current in each shading cases

Rows	Corner		Center		Frame		SN		SW		LN		LW	
	I_R	I_{Inj}	I_R	I_{Inj}	I_R	I_{Inj}	I_R	I_{Inj}	I_R	I_{Inj}	I_R	I_{Inj}	I_R	I_{Inj}
Row 1	5.88	0.38	6.25	0.00	3.63	2.63	4.75	1.50	5.75	0.50	4.75	1.50	4.00	2.25
Row 2	6.25	0.00	4.00	2.25	4.75	1.50	5.38	0.88	5.38	0.88	4.63	1.63	3.38	2.88
Row 3	6.25	0.00	4.25	2.00	5.50	0.75	5.00	1.25	5.00	1.25	5.13	1.13	4.63	1.63
Row 4	6.25	0.00	5.38	0.88	5.25	1.00	6.25	0.00	5.63	0.63	6.25	0.00	4.63	1.63
Row 5	5.25	1.00	6.25	0.00	2.75	3.50	6.25	0.00	5.00	1.25	6.25	0.00	6.25	0.00

Table 2. Power output of conventional and proposed method

S.NO	Shading Type	Maximum Current		Maximum Power		Efficiency	
		IC	IP	PC	PP	N	N
1	Healthy	5.5	5.5	250	250	100.0%	100.0%
2	Corner	4.62	5.5	210	250	84.0%	100.0%
3	Centre	3.52	5.5	160	250	64.0%	100.0%
4	Frame	2.42	5.5	110	250	44.0%	100.0%
5	SN	4.18	5.5	190	250	76.0%	100.0%
6	SW	4.4	5.5	200	250	80.0%	100.0%
7	LN	4.07	5.5	185	250	74.0%	100.0%
8	LW	2.97	5.5	135	250	54.0%	100.0%

For installations in settings where shading is inevitable, this makes the technique especially useful. All things considered, the findings show that the proposed current compensation approach is a workable and efficient way to improve PV system performance and dependability. Further algorithm optimization and validation by field testing could be part of future work to verify the algorithm's performance in practical settings. The encouraging findings of this work imply that the proposed approach, which provides a more robust and effective way to controlling partial shading and enhancing overall system performance, may be very important in the next generation of PV systems.

4 Conclusion

This study presents a novel current compensation method to mitigate mismatch losses in photovoltaic (PV) systems caused by uneven irradiance. Using real-time irradiance measurements from light sensors on each PV panel, the method dynamically adjusts current injection across the array, ensuring uniform current distribution without interruptions. Tested under various shading patterns using MATLAB/Simulink simulations, the proposed method demonstrated significant improvements in performance compared to the conventional Total Cross-Tied (TCT) configuration. It effectively reduced mismatch losses, maintained higher power output, and improved overall system efficiency across all shading conditions. The proposed method's key advantages include real-time adjustments, elimination of blackout periods, and a simplified system setup by removing the need for switches and current sensors. This dynamic adjustment ensures optimal performance even under rapidly changing conditions, making it robust and adaptable. In summary, the proposed current compensation method offers a practical and efficient solution for enhancing PV system performance and reliability, particularly in partially shaded environments. Its ability to manage irradiance variations dynamically holds promise for improving solar energy systems' efficiency and reliability, contributing to broader renewable energy adoption.

References

1. S. T. Bryant, K. Straker, and C. Wrigley, "The need for sectoral transition design: A case of the shift to renewable energy," Technol Forecast Soc Change, vol. 198, p. 122930, Jan. 2024, doi: 10.1016/j.techfore.2023.122930.
2. P. Viebahn, O. Soukup, S. Samadi, J. Teubler, K. Wiesen, and M. Ritthoff, "Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables," Renewable and Sustainable Energy Reviews, vol. 49, pp. 655–671, Sep. 2015, doi: 10.1016/j.rser.2015.04.070.
3. F. Wang, L. Zhuang, S. Cheng, Y. Zhang, and S. Cheng, "Spatiotemporal variation and convergence analysis of China's regional energy security," Renewable and Sustainable Energy Reviews, vol. 189, p. 113923, Jan. 2024, doi: 10.1016/j.rser.2023.113923.
4. Y. Yang, P. E. Campana, and J. Yan, "Potential of unsubsidized distributed solar PV to replace coal-fired power plants, and profits classification in Chinese cities," Renewable and Sustainable Energy Reviews, vol. 131, p. 109967, Oct. 2020, doi: 10.1016/j.rser.2020.109967.
5. M. Aghaei, N. M. Kumar, A. Eskandari, H. Ahmed, A. K. V. de Oliveira, and S. S. Chopra, "Solar PV systems design and monitoring," in Photovoltaic Solar Energy Conversion, Elsevier, 2020, pp. 117–145. doi: 10.1016/B978-0-12-819610-6.00005-3.
6. D. Prince Winston, K. Ganesan, P. K. B, D. Samithas, and C. B. Baladhanautham, "Experimental investigation on output power enhancement of partial shaded solar photovoltaic system," Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, pp. 1–17, Jun. 2020, doi: 10.1080/15567036.2020.1779872.
7. K. Lappalainen and S. Valkealahti, "Effects of irradiance transition characteristics on the mismatch losses of different electrical PV array configurations," IET Renewable Power Generation, vol. 11, no. 2, pp. 248–254, Feb. 2017, doi: 10.1049/iet-rpg.2016.0590.
8. K. Lappalainen and S. Valkealahti, "Photovoltaic mismatch losses caused by moving clouds," Solar Energy, vol. 158, pp. 455–461, Dec. 2017, doi: 10.1016/j.solener.2017.10.001.
9. T. N. Prasad et al., "Power management in hybrid ANFIS PID based AC–DC microgrids with EHO based cost optimized droop control strategy," Energy Reports, vol. 8, pp. 15081–15094, Nov. 2022, doi: 10.1016/j.egyr.2022.11.014.
10. B. Aljafari, P. K. Balachandran, D. Samithas, and S. B. Thanikanti, "Solar photovoltaic converter controller using opposition-based reinforcement learning with butterfly optimization algorithm under partial shading conditions," Environmental Science and Pollution Research, vol. 30, no. 28, pp. 72617–72640, May 2023, doi: 10.1007/s11356-023-27261-1.
11. V. V. Ramana, A. Mudlapur, R. V. Damodaran, B. Venkatesaperumal, and S. Mishra, "Global Peak Tracking of Photovoltaic Array Under Mismatching Conditions Using Current Control," IEEE Transactions on Energy Conversion, vol. 34, no. 1, pp. 313–320, Mar. 2019, doi: 10.1109/TEC.2018.2873667.
12. A. Mohapatra, B. Nayak, P. Das, and K. B. Mohanty, "A review on MPPT techniques of PV system under partial shading condition," Renewable and Sustainable Energy Reviews, vol. 80, pp. 854–867, Dec. 2017, doi: 10.1016/j.rser.2017.05.083.
13. A. Srinivasan, S. Devakirubakaran, and B. Meenakshi Sundaram, "Mitigation of mismatch losses in solar PV system – Two-step reconfiguration approach," Solar Energy, vol. 206, pp. 640–654, Aug. 2020, doi: 10.1016/j.solener.2020.06.004.
14. S. Alwar, D. Samithas, M. S. Boominathan, P. K. Balachandran, and L. Mihet-Popa, "Performance Analysis of Thermal Image Processing-Based Photovoltaic Fault Detection and PV Array Reconfiguration—A Detailed Experimentation," Energies (Basel), vol. 15, no. 22, p. 8450, Nov. 2022, doi: 10.3390/en15228450.
15. S. B. Thanikanti, P. K. B, D. S, B. Aljafari, and I. Colak, "A dynamic mismatch loss mitigation algorithm with dual input dual output converter for solar PV systems," Solar Energy Materials and Solar Cells, vol. 251, p. 112163, Mar. 2023, doi: 10.1016/j.solmat.2022.112163.
16. M. Durango-Flórez, D. González-Montoya, L. A. Trejos-Grisales, and C. A. Ramos-Paja, "PV Array Reconfiguration Based on Genetic Algorithm for Maximum Power Extraction and Energy Impact Analysis," Sustainability, vol. 14, no. 7, p. 3764, Mar. 2022, doi: 10.3390/su14073764.
17. T. S. Babu, J. P. Ram, T. Dragicevic, M. Miyatake, F. Blaabjerg, and N. Rajasekar, "Particle Swarm Optimization Based Solar PV Array Reconfiguration of the Maximum Power Extraction Under Partial Shading Conditions," IEEE Trans Sustain Energy, vol. 9, no. 1, pp. 74–85, Jan. 2018, doi: 10.1109/TSTE.2017.2714905.
18. D. Prince Winston, S. Kumaravel, B. Praveen Kumar, and S. Devakirubakaran, "Performance improvement of solar PV array topologies during various partial shading conditions," Solar Energy, vol. 196, pp. 228–242, Jan. 2020, doi: 10.1016/j.solener.2019.12.007.
19. S. Devakirubakaran, R. Verma, C. Bharatiraja, and L. Mihet-Popa, "Performance Evaluation of Static

PV Array Configurations for Mitigating Mismatch Losses," IEEE Access, pp. 1–1, 2023, doi: 10.1109/ACCESS.2023.3274684.

20. S. R. Pendem and S. Mikkili, "Modeling, simulation and performance analysis of solar PV array configurations (Series, Series–Parallel and Honey-Comb) to extract maximum power under Partial Shading Conditions," Energy Reports, vol. 4, pp. 274–287, Nov. 2018, doi: 10.1016/j.egyr.2018.03.003.
21. S. Mohammadnejad, A. Khalafi, and S. M. Ahmadi, "Mathematical analysis of total-cross-tied photovoltaic array under partial shading condition and its comparison with other configurations," Solar Energy, vol. 133, pp. 501–511, Aug. 2016, doi: 10.1016/j.solener.2016.03.058.
22. G. Sagar, D. Pathak, P. Gaur, and V. Jain, "A Su Do Ku puzzle based shade dispersion for maximum power enhancement of partially shaded hybrid bridge-link-total-cross-tied PV array," Solar Energy, vol. 204, pp. 161–180, Jul. 2020, doi: 10.1016/j.solener.2020.04.054.
23. C.-E. Ye, C.-C. Tai, and Y.-P. Huang, "Disperse Partial Shading Effect of Photovoltaic Array by Means of the Modified Complementary SuDoKu Puzzle Topology," Energies (Basel), vol. 16, no. 13, p. 4910, Jun. 2023, doi: 10.3390/en16134910.
24. B. Dhanalakshmi and N. Rajasekar, "Dominance square based array reconfiguration scheme for power loss reduction in solar PhotoVoltaic (PV) systems," Energy Convers Manag, vol. 156, pp. 84–102, Jan. 2018, doi: 10.1016/j.enconman.2017.10.080.
25. B. Dhanalakshmi and N. Rajasekar, "A novel Competence Square based PV array reconfiguration technique for solar PV maximum power extraction," Energy Convers Manag, vol. 174, pp. 897–912, Oct. 2018, doi: 10.1016/j.enconman.2018.08.077.
26. A. Srinivasan et al., "L-Shape Propagated Array Configuration With Dynamic Reconfiguration Algorithm for Enhancing Energy Conversion Rate of Partial Shaded Photovoltaic Systems," IEEE Access, vol. 9, pp. 97661–97674, 2021, doi: 10.1109/ACCESS.2021.3094736.
27. S. K. Cherukuri et al., "Power Enhancement in Partial Shaded Photovoltaic System Using Spiral Pattern Array Configuration Scheme," IEEE Access, vol. 9, pp. 123103–123116, 2021, doi: 10.1109/ACCESS.2021.3109248.
28. X. H. Nguyen and M. P. Nguyen, "Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink," Environmental Systems Research, vol. 4, no. 1, p. 24, Dec. 2015, doi: 10.1186/s40068-015-0047-9.
29. T. Ma, W. Gu, L. Shen, and M. Li, "An improved and comprehensive mathematical model for solar photovoltaic modules under real operating conditions," Solar Energy, vol. 184, pp. 292–304, May 2019, doi: 10.1016/j.solener.2019.03.089.