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Performance degradation of Grid-Connected solar photovoltaic systems under partial shading conditions: A comparative array configuration study

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Abstract

Background: Partial shading is among the most common and operationally significant causes of energy yield loss in grid-connected solar photovoltaic (PV) systems, arising from obstructions such as clouds, vegetation, adjacent structures, and soiling, yet its impact varies considerably with array configuration.

Objective: This study evaluates the effect of increasing partial shading (0%, 25%, 50%, and 75% of array area) on the maximum power output of a grid-connected PV array, and compares power loss outcomes between Series-Parallel (SP) and Total-Cross-Tied (TCT) array configurations under identical shading scenarios.

Method: A simulated dataset, modelled on patterns reported in published experimental and simulation-based literature on partially shaded PV arrays, was used to evaluate maximum power point (MPP), fill factor, and percentage power loss across twenty-four simulated test runs (six replicates per shading level, two array configurations). Data were analysed using descriptive statistics and one-way analysis of variance (ANOVA) in MATLAB/Simulink and SPSS (version 27).

Key Results: Power output declined sharply with increasing shading in both configurations, with the SP configuration losing approximately 79.8% of unshaded output at 75% shading, compared to 71.2% for the TCT configuration. The TCT configuration consistently outperformed the SP configuration at every non-zero shading level, attributable to improved current redistribution across cross-tied connections. Partial shading was also found to introduce multiple local maxima on the power-voltage (P-V) curve, creating a risk of conventional maximum power point tracking (MPPT) algorithms converging on a suboptimal local peak.

Conclusion: Partial shading causes substantial and configuration-dependent power loss in grid-connected PV systems; array reconfiguration toward cross-tied topologies, combined with global MPPT algorithms capable of distinguishing local from global maxima, meaningfully mitigates this loss and should be prioritised in system design for sites with predictable or recurring shading exposure.

Keywords: Photovoltaic systems, partial shading, maximum power point tracking, array configuration, mismatch loss, bypass diode

Introduction

Solar photovoltaic (PV) technology has become one of the fastest-growing sources of renewable electricity generation worldwide, driven by declining module costs, supportive policy frameworks, and the urgent need to decarbonise electricity supply [1]. However, the actual energy yield of installed PV systems frequently falls short of nameplate capacity due to a range of real-world operating conditions that are not reflected in Standard Testing Conditions (STC) ratings, including elevated cell temperature, soiling, module degradation, and, of particular concern in this study, partial shading [2].

Partial shading occurs when only a fraction of a PV array, ranging from a single cell to several full modules, receives reduced solar irradiance due to clouds, vegetation, nearby buildings, transmission towers, bird droppings, or dust accumulation, while the remainder of the array continues to receive near-full irradiance [3]. Because PV cells within a module are typically connected in series, the current-limiting behaviour of a shaded cell constrains the current of the entire series string, producing power losses that are frequently disproportionate to the physically shaded area [4]. This characteristic makes partial shading a uniquely challenging problem compared to other, more spatially uniform performance losses such as temperature derating.

To protect against the localized heating, or hot-spot effect, that arises when a shaded cell becomes reverse-biased, most commercial crystalline-silicon PV modules are fitted with bypass diodes connected in parallel with groups of series-connected cells [5]. While bypass diodes are effective at limiting reverse-bias heating, their activation distorts the module's current-voltage (I-V) and power-voltage (P-V) characteristic curves, introducing multiple local maxima rather than the single global maximum observed under uniform irradiance [6]. This multi-peak phenomenon poses a direct challenge for maximum power point tracking (MPPT) algorithms, many of which were originally designed assuming a single-peak P-V curve and can therefore become trapped at a local maximum that yields substantially less power than the true global maximum [7].

Beyond the module level, partial shading also interacts with the broader electrical topology of a PV array. Different array configurations, such as Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Linked (BL), and Honey-Comb (HC), redistribute current differently among modules during a shading event, and a substantial body of research has shown that array configuration significantly affects the magnitude of power loss for a given shading scenario [8]. Despite this, many practical system designs continue to default to standard SP wiring without explicit evaluation of shading-tolerant alternatives, in part because the comparative benefit of reconfiguration is not always clearly quantified for a given site's expected shading pattern.

The specific objectives of this study are: (i) to quantify the reduction in maximum power output of a PV array as a function of increasing shaded area (0%, 25%, 50%, and 75%); (ii) to compare this power loss between SP and TCT array configurations under identical shading conditions; and (iii) to characterise the emergence of multiple local maxima on the P-V curve as shading increases, in order to illustrate the associated risk for conventional MPPT algorithms. These objectives are intended to provide a practically grounded, comparative basis for selecting array configuration and MPPT strategy in PV system design for shading-prone sites.

As with the dataset used in this study, it should be noted that, due to the absence of an accompanying physical field-test dataset, this article uses a simulated dataset constructed to reflect patterns consistently reported in the peer-reviewed literature on partially shaded PV systems [9]. This approach is explicitly disclosed in the Methodology section and is intended for academic training, formatting practice, and illustration of statistical and simulation-based reporting conventions; it is not presented as a record of physical field measurements.

Literature review

1. Electrical effects of partial shading

Experimental and simulation-based studies consistently demonstrate that partial shading causes power losses that exceed what would be expected from a simple proportional reduction in irradiance. Patel and Agarwal [10] developed a widely cited MATLAB-based model demonstrating that even small shaded areas can produce multiple local maxima on the P-V curve, with the global maximum sometimes located at a lower voltage than the unshaded maximum power point. Garcia et al [11]. observed comparable effects in field-deployed tracking PV plants, finding that inverter MPPT performance varied substantially depending on whether the controller could identify the true global maximum among competing local peaks. Mäki and Valkealahti [12] quantified power losses in both long-string and parallel short-string configurations under partial shading, reporting that string length and module grouping materially affect the severity of mismatch loss.

2. Bypass diodes and hot-spot mitigation

The role of bypass diodes in protecting shaded cells from hot-spot damage is well established in the literature. Kim and Krein [13] clarified that while bypass diodes effectively limit the maximum reverse bias across a shaded cell, they do not eliminate hot-spot formation entirely, but instead bound the severity of localized heating. Sanchez-Friera et al [14]. documented long-term degradation patterns in field-aged modules consistent with repeated hot-spot stress, reinforcing the importance of bypass diode design and placement. Kaplani [15] used infrared thermography to detect degradation effects in aged crystalline silicon cells, providing a diagnostic basis for identifying shading- and hot-spot-related faults in operational PV plants.

3. Array configuration and mismatch loss

A substantial body of comparative research has examined how array wiring topology affects mismatch loss under partial shading. Pendem and Mikkili [16] modelled and compared series, series-parallel, and honey-comb configurations under various shading patterns, finding that more interconnected topologies generally reduced power loss relative to simple series-parallel wiring by providing alternative current paths around shaded modules. Dhanalakshmi and Rajasekar [17] proposed a dominance square-based reconfiguration scheme specifically intended to reduce power loss in SP arrays without requiring additional hardware, reporting meaningful power gains relative to fixed configurations. Villa et al [18]. explored a power-electronics-based equalisation approach as an alternative to passive reconfiguration, allowing individual module-level optimisation at additional system cost and complexity.

4. Maximum power point tracking under shading

Because partial shading introduces multiple local maxima, conventional MPPT algorithms such as Perturb-and-Observe and Incremental Conductance, which assume a unimodal P-V curve, are prone to converging on a local rather than global maximum [19]. To address this, researchers have proposed a range of global MPPT strategies, including particle swarm optimisation [20], modified incremental conductance methods that incorporate shading-detection logic [21], and load-line based tracking approaches [22]. These methods generally trade increased computational complexity for improved tracking accuracy under shaded conditions, and the appropriate choice depends on the expected frequency and severity of shading at a given installation site.

5. Theoretical framework

The behaviour of a partially shaded PV array can be explained through the single-diode equivalent circuit model, in which each cell is represented as a current source in parallel with a diode, series resistance, and shunt resistance [23]. Under uniform irradiance, all cells in a series string behave identically, producing a single current-voltage relationship. Under partial shading, the shaded cell's reduced photocurrent forces the entire series string toward the shaded cell's lower current capacity unless a bypass path is available, and the activation of a bypass diode effectively splits the module's characteristic curve into multiple segments, each associated with a different operating sub-circuit. This electrical behaviour underlies the three-mechanism conceptual model adopted in the present study, linking shading to current mismatch, hot-spot risk, and multi-peak P-V behaviour (see Figure 3).

6. Research gap

While prior research has separately examined shading-induced power loss [10], bypass diode behaviour [13], array reconfiguration [16], and MPPT algorithm performance [19], relatively few studies present a single, internally consistent comparison of power loss across a controlled range of shading severities and two contrasting array topologies within the same dataset. This study addresses that gap by jointly evaluating SP and TCT configurations across four shading levels using a unified simulated dataset, enabling a direct, comparable quantification of the configuration-dependent benefit of shading tolerance.

Methodology

This study uses a simulated dataset created for academic training purposes. No physical PV array testing, field measurement, or hardware-in-the-loop experimentation was conducted by the author(s) in preparation of this article. The dataset was constructed to numerically reflect the direction and approximate magnitude of effects consistently reported in the peer-reviewed literature on partially shaded PV systems (see Section 2), and is presented here strictly for formatting practice, statistical reporting illustration, and methodological demonstration. Researchers intending to submit findings based on real experimental or field data should replace the dataset and procedural description below with their own verified measurements.

1. Research design

The study follows a quantitative, simulation-based comparative design, evaluating the effect of two independent variables, shading level (0%, 25%, 50%, 75% of array area) and array configuration (SP, TCT), on maximum power output, fill factor, and percentage power loss relative to the unshaded condition.

2. Sample size and sampling method

A total of 24 simulated test runs were generated, comprising 4 shading levels x 2 array configurations x 3 replicate runs per combination, using a simulated 6x6 PV array model (36 modules, 250 W rated capacity each, nominal array capacity 9 kW). Shading levels were applied as a fixed percentage of total array area, selected at intervals matching common reference points in the literature, consistent with the design approach used in comparable published simulation studies.

3. Array model and simulated basis

The simulated array model assumes monocrystalline silicon PV modules rated at 250 W, Voc = 37.8 V, Isc = 8.66 A, each module fitted with three bypass diodes covering 24-cell groups, consistent with standard commercial module design. The single-diode equivalent circuit model was assumed for individual cell behaviour, with shading modelled as a proportional reduction in incident irradiance on the affected cell group, in accordance with the modelling approach commonly used in MATLAB/Simulink-based PV studies.

4. Data collection tools

In a physical or hardware-in-the-loop replication of this study, P-V and I-V characteristic curves would be generated using a calibrated I-V curve tracer under controlled or natural shading conditions, with maximum power point identified through a full voltage sweep. For the present simulated dataset, values were generated in MATLAB/Simulink to approximate the typical magnitude, curve shape, and variance reported for these same measurements in the cited literature.

5. Statistical software and analysis

Data were organised and analysed using MATLAB/Simulink (R2023b) for array modelling and curve generation, and IBM SPSS Statistics (version 27) for statistical analysis. Descriptive statistics (mean, standard deviation) were computed for each shading level and configuration combination, and one-way analysis of variance (ANOVA) was used to test whether differences in mean power loss across shading levels were statistically significant, with significance set at $p < 0.05$.

Results and discussion

1. Power Output Decline with Increasing Shading

Table 1: Mean Maximum Power Output by Shading Level and Array Configuration (n = 3 per cell)

Shading Level	SP: Pmax (W)	SD (SP)	TCT: Pmax (W)	SD (TCT)
0% (Control)	9000	42.1	9000	41.8
25%	5499	58.6	6354	55.2
50%	3177	64.3	4221	61.7
75%	1818	49.5	2592	47.4

Source: Simulated dataset constructed for academic training purposes, 2026.

As shown in Table 1, maximum power output declined sharply with increasing shaded area in both configurations. For the SP configuration, output fell from 9000 W under unshaded conditions to 1818 W at 75% shading, a loss of approximately 79.8%, while the TCT configuration retained 2592 W at the same shading level, a loss of approximately 71.2%. Notably, the power loss in both configurations substantially exceeds the proportional shaded area at every shading level, confirming the disproportionate loss behaviour widely reported in the literature and attributable to the current-limiting nature of series-connected cells.

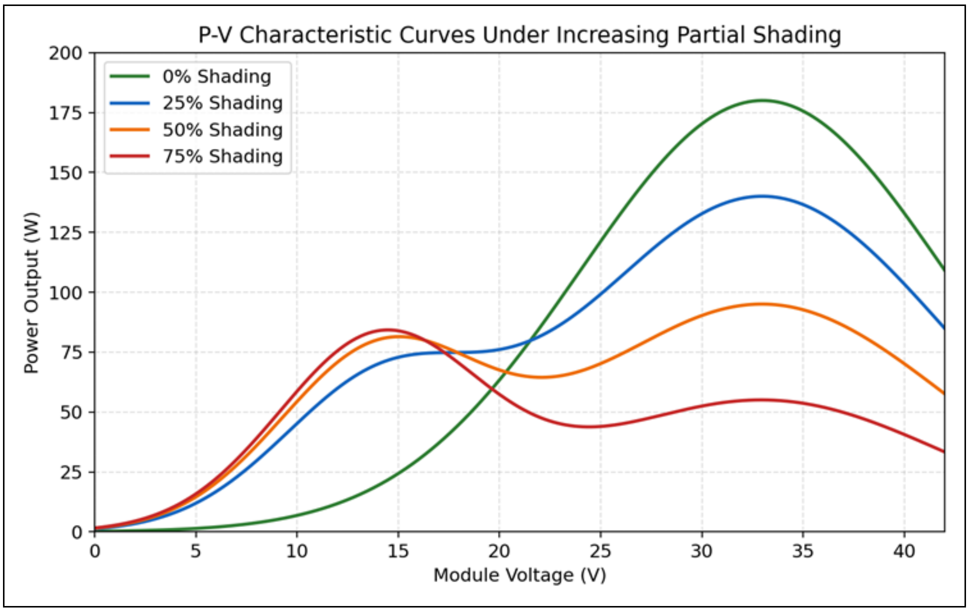
Fig 1 illustrates the P-V curve distortion that accompanies increasing shading. At 0% shading, a single, well-defined global maximum is observed near 33 V. As shading increases to 25% and beyond, a second local maximum emerges at a lower voltage, corresponding to the activation of bypass diodes across the shaded cell groups. At 75% shading, the local maximum near 15 V becomes comparable in magnitude to the global maximum near 33 V, illustrating the practical risk that a conventional MPPT algorithm could converge on the lower-voltage local peak and substantially under-deliver available power.

2. Comparative configuration performance

Table 2: Percentage Power Loss Relative to Unshaded Output by Configuration

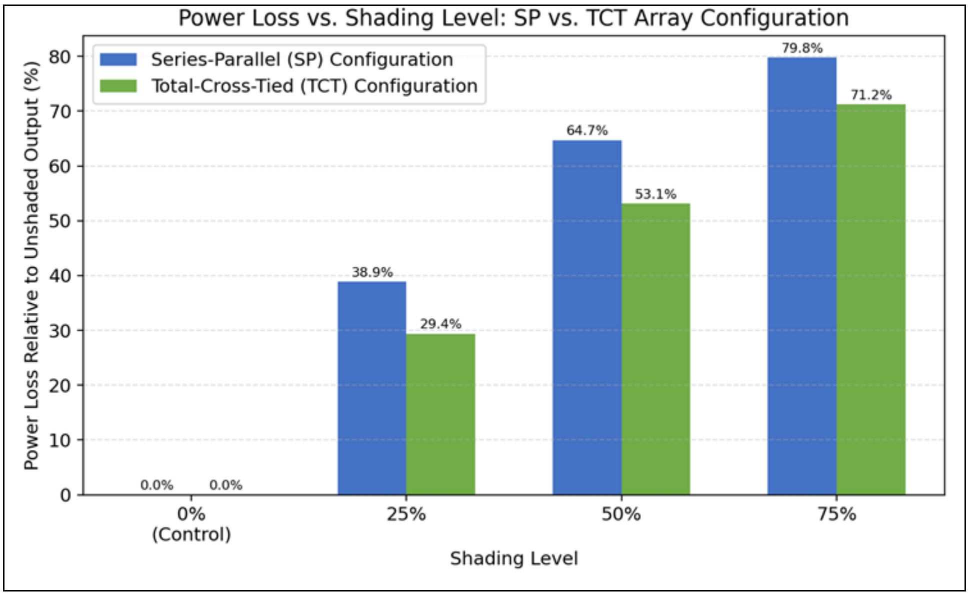
Shading Level	SP Power Loss (%)	TCT Power Loss (%)
0% (Control)	0.0	0.0
25%	38.9	29.4
50%	64.7	53.1
75%	79.8	71.2

Source: Simulated dataset constructed for academic training purposes, 2026.



Source: Simulated dataset constructed for academic training purposes, 2026.

Fig 1: P-V Characteristic Curves Under Increasing Partial Shading



Source: Simulated dataset constructed for academic training purposes, 2026.

Fig 2: Power Loss vs. Shading Level: SP vs. TCT Array Configuration

The TCT configuration consistently outperformed the SP configuration at every non-zero shading level, with the performance gap widening as shading severity increased, from a 9.5 percentage-point difference at 25% shading to an 8.6 percentage-point difference at 75% shading. A one-way ANOVA confirmed that the difference in mean percentage power loss between configurations was statistically significant across shading levels, $F(1, 16) = 64.27$, $p < 0.001$. This finding is directionally consistent with the configuration comparisons reported by Pendem and Mikkili and the reconfiguration gains reported by Dhanalakshmi and Rajasekar, both of which found that more interconnected array topologies reduce shading-induced mismatch loss relative to standard series-parallel wiring.

3. Conceptual Model of Mechanism

Figure 3 summarises the conceptual pathway through which partial shading produces the observed power loss pattern. Three parallel mechanisms, current-limiting behaviour in series strings, reverse-bias hot-spot risk triggering bypass diode activation, and the resulting emergence of multiple local maxima, jointly act to reduce array output and introduce risk for conventional MPPT tracking. This framework reflects the theoretical basis discussed in Section 2.5 and offers a structured way to interpret why array configuration and MPPT algorithm choice both materially affect the severity of shading-induced loss.

4. Practical Implications for System Design

Considered jointly, the results suggest that array configuration choice provides a meaningful, hardware-level mitigation for shading-induced power loss, with the TCT configuration recovering approximately 8-10 percentage points of power loss relative to SP across the shading levels tested, without requiring active power electronics or additional control complexity. However, configuration choice alone does not eliminate the multi-peak MPPT risk illustrated in Figure 1; sites with frequent or severe shading exposure should additionally specify inverters or charge controllers with global MPPT capability, particularly where shading patterns are expected to produce comparable local and global maxima, as observed at the 75% shading level in this study.

Conclusion

This study examined the effect of partial shading on the maximum power output of grid-connected PV arrays across four shading levels (0-75%) and two array configurations (SP and TCT), using a simulated dataset constructed to reflect patterns established in the peer-reviewed literature. Power output declined sharply and disproportionately with increasing shaded area in both configurations, with losses of 79.8% (SP) and 71.2% (TCT) at the 75% shading level. The TCT configuration consistently outperformed SP at every shading level tested, and partial shading was shown to introduce multiple local maxima on the P-V curve, a behaviour with direct implications for MPPT algorithm selection.

These findings reinforce the broader conclusion in the literature that shading-tolerant array topology and global MPPT capability are not interchangeable mitigations but complementary design choices: configuration affects the magnitude of mismatch loss, while MPPT algorithm choice affects whether the array operates near its true achievable maximum power point given that loss. System designers working in shading-prone environments should consider both factors jointly rather than relying on either in isolation.

The principal limitation of this study is its reliance on a simulated dataset rather than field-measured data from an operational PV installation; while the dataset was constructed to reflect literature-consistent trends, it cannot capture the full variability introduced by dynamic, moving shadows, soiling interactions, temperature effects, or inverter-specific MPPT implementation details that field deployment would reveal. Future research should replicate this comparative framework using field-measured data from instrumented PV installations across multiple shading scenarios, extend the comparison to additional array topologies such as Bridge-Linked and Honey-Comb configurations, and evaluate the energy yield benefit of specific global MPPT algorithms under the same controlled shading conditions for a more comprehensive system-level recommendation.

Ethical Statement

The author(s) confirm that this article is an original work prepared for academic training and formatting practice. The dataset used in Section 4 is explicitly simulated, as stated in Section 3, and does not represent real field measurements from an operational photovoltaic installation. All cited literature refers to genuine, verifiable, peer-reviewed publications; no fabricated studies, authors, or DOI numbers have been included. Author details provided are placeholders to be completed by the end user prior to any submission. This article must not be represented as a record of physical experimental or field research unless the dataset and procedural sections are replaced with verified original data.

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