Optimizing Photovoltaic System Performance in Partially Shaded Conditions: A Comprehensive Review of Mitigation Strategies

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***Abstract*—Photovoltaic (PV) systems have become a vital component in the quest for sustainable energy solutions. However, partial shading significantly hampers their efficiency, causing notable power losses. This comprehensive review evaluates various strategies to mitigate the adverse effects of partial shading on PV systems. Key approaches include the integration of bypass diodes, advanced maximum power point tracking (MPPT) algorithms, and module-level power electronics such as power optimizers and microinverters. These techniques enable individual modules to operate independently at their optimal power points, enhancing overall system efficiency. Additionally, system design optimizations, including layout adjustments and shading analysis tools, are critical in maximizing energy yield. The review also compares different MPPT methods, highlighting their strengths and limitations under partial shading conditions. Despite advancements, the literature indicates a need for further research into combining multiple optimization techniques to achieve superior performance in complex shading scenarios. This review aims to provide a roadmap for future research, emphasizing the importance of integrated and advanced strategies for optimizing PV system performance under partially shaded conditions.**

***Index Terms*—Partial shading, photovoltaic systems, MPPT algorithms, bypass diodes, power optimizers, microinverters, shading mitigation strategies.**

I. INTRODUCTION

Photovoltaic (PV) systems have emerged as a promising renewable energy technology, offering a sustainable solution to the world's increasing energy demand [1]. However, partially shaded situations can have a substantial impact on PV system performance, leading to decreased production and efficiency [2]. Several factors, including surrounding structures, trees, clouds, and even dust buildup on the panel, can cause partial shadowing [3], [4]. Significant research has been done recently to try to mitigate the negative effects that partial shade has on the performance of PV systems [5], [6]. Optimizing PV system performance under partial shade situations poses several fundamental challenges, one of which is the inherent power loss in series-connected traditional PV systems [4], [7], [8]. Traditional PV systems are usually connected in series, meaning even a small amount of shade on the array causes a significant loss of power [9]. To address this issue, researchers have proposed innovative approaches such as bypass diodes, maximum power point tracking (MPPT) algorithms, and distributed MPPT techniques [10], [11].

Additionally, developments in module-level power electronics, including power optimizers and microinverters, have shown promising results in reducing the effects of partial shading [12]. These solutions increase the PV system's overall efficiency and reliability by allowing individual modules to function independently at their maximum power point. In addition to technological solutions, this review also discusses the importance of system design, layout optimization, and shading analysis tools in maximizing energy yield and return on investment. Furthermore, maximum power point tracking (MPPT) techniques are crucial in optimizing the performance of PV systems under partial shading conditions (PSCs). Various MPPT methods have been developed, each with its own advantages and challenges. The table-I provides a comparison of different MPPT techniques under PSCs.

Furthermore, maximum power point tracking (MPPT) techniques are crucial in optimizing the performance of PV systems under PSC. Various MPPT methods have been developed, each with its own advantages and challenges. The following table-I provides a comparison of different MPPT techniques under PSCs.

Table-I: Comparison of Different MPPT Techniques under PSCs

MPPT Technique	*Description*	*Advantages*	*Disadvantages*
Perturb and Observe (P&O)	Iteratively adjusts voltage to find MPP	Simple implementation, low cost	May fail under rapidly changing conditions
Incremental Conductance	Uses the derivative of power to voltage ratio	Accurate under steady-state conditions	Complex, higher computational requirements
Particle Swarm Optimization	Swarm intelligence-based algorithm for global MPP	Effective in finding global MPP under PSCs	High computational complexity, slower convergence
Fuzzy Logic Control	Uses fuzzy logic to handle uncertainties and non-linearities	Good performance under dynamic conditions	Requires expert knowledge for rule set design
Neural Network	Uses artificial neural networks to predict MPP	High accuracy, adaptive learning capability	Requires extensive training, computationally intensive
Genetic Algorithm	Evolutionary algorithm to search for MPP	Robust performance under complex PSCs	Slow convergence, high computational cost

Choosing the appropriate maximum power point tracking (MPPT) technique under PSCs is crucial for optimizing the performance of photovoltaic (PV) systems. The decision-making process involves assessing the shading pattern and the specific requirements of the system, such as response time and complexity of shading. The Figure 1 flowchart illustrates the decision-making process for selecting MPPT techniques under various PSC.

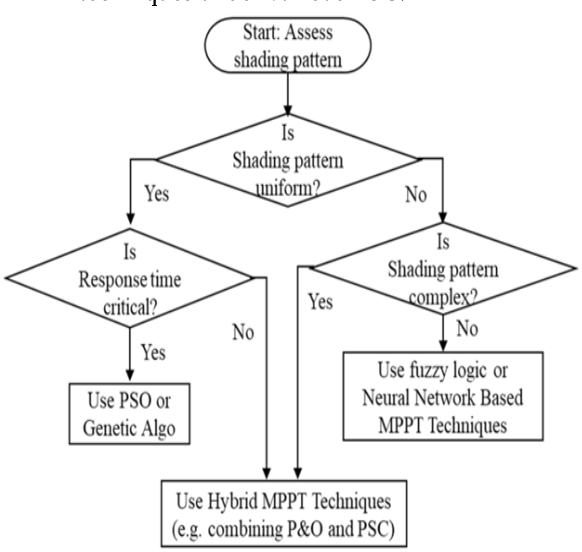

Figure 1: Flowchart for Selecting MPPT Techniques under PSCs

These MPPT techniques have been tested and implemented in various PV systems with significant improvements in energy yield and efficiency. For instance, the Fuzzy Logic Control method has demonstrated excellent performance under dynamic shading conditions due to its ability to handle uncertainties and non-linearities [13], [14]. Conversely, Particle Swarm Optimization (PSO) has been particularly effective in scenarios with complex shading patterns, despite its higher computational requirements.

Furthermore, considerations such as cost-effectiveness, scalability, and compatibility with existing PV installations are crucial factors to be taken into account when implementing mitigation strategies. [15] provides PV array Reconfiguration techniques based on the Modified Harris Hawks Optimizer algorithm and Static Shade Dispersion Physical Array Relocation algorithm for reducing the detrimental effects of PSCs on PV system performance. By integrating static and dynamic reconfiguration strategies, [16] tackles the important problem of mismatch losses inPV arrays under partial shade situations. By taking short-circuit current levels into account, the method reduces the number of switches and sensors needed. Experiments carried out under eight distinct partial shading patterns show how efficient the suggested approach is.

[17] reports on the difficulties with MPPT in PSCs while using particle swarm optimization (PSO) as an optimization technique to improve the performance of solar PV systems. The study compares the perturb and observe (P&O) and Incremental Conductance (INC) algorithms with PSO as a proposed solution. A Grey Wolf Optimization (GWO) -based MPPT algorithm was presented by [18] for PV systems that are operating in PSCs. Better tracking speed and efficiency of the GWO-based algorithm demonstrate how well it performs when compared to more traditional techniques like P&O and PSO. Similarly, [19] presented an Markov Decision Process (MDP)-based approach for dynamic MPPT under PSCs, demonstrating significant improvements in maximum power compared to traditional techniques. However, these studies focus on individual optimization algorithms without exploring the potential synergies or combined use of multiple techniques.

Furthermore, a two-step approach combining static and dynamic reconfiguration strategies was presented by [16] to reduce mismatch losses in PV arrays under partial shadowing. While this approach offers practical solutions, there is potential for further optimization by incorporating advanced MPPT algorithms like GWO or MDP-based techniques into the reconfiguration process. Additionally, while [20] presented a novel MPPT approach based on the flower pollination algorithm improved by Levy flight, little research has been done on how to combine these evolutionary algorithms with other optimization strategies currently in use, such as GWO or MDP-based techniques, to improve MPPT performance in partial shading scenarios.

The literature gap identified from the research revolves around the need for further research into the integration and enhancement of optimization techniques for MPPT in PV systems under PSCs. While several studies have proposed novel MPPT algorithms, such as GWO and MDP-based approaches, there remains a gap in the literature regarding the comparison and combination of these techniques to achieve even greater efficiency and robustness in MPPT under complex shading scenarios. This comprehensive review aims to analyze and evaluate the various mitigation strategies. By synthesizing existing knowledge and identifying gaps in research. This review article attempts to offer a road map for future research paths in the area of optimizing PV system performance under partially shaded settings through a thorough analysis of the state-of-the-art approaches and techniques.

The current review paper's primary contributions include

i. Gave a thorough and up-to-date overview of the various configuration techniques for solar photovoltaic systems.
ii. Current discussion of the causes of the difficulties with partial shadowing in photovoltaic systems
iii. Examined the efficacy of the methods being used at the moment to lessen the negative effects of partial shadowing on the performance of solar systems.
iv. Discussed the many software- and hardware-based strategies and solutions used for the PV system's partial shading.
v. Discussed the issues of practicality and implementation that arise when implementing mitigation techniques in actual solar systems.

There are six sections in this article. The principles of partial shading in PV systems and the difficulties it creates are covered in Section II. Section III discusses the mitigation strategies. Section IV elaborates on the classification of mitigation strategies for partial shading in solar photovoltaic systems. Section V presents the challenges and future directions. There are closing thoughts in Section VI.

II. FUNDAMENTALS OF PARTIAL SHADING IN PV SYSTEMS:

Partial shadowing is a frequent phenomenon in solar PV systems. where certain portions of the PV array are shaded while others remain exposed to sunlight. Figure 2(a) depicts a PV string comprising four modules operating without any shading. All modules contribute to the power output optimally. Figure 2(b) shows a PV string with partial shading affecting only one of the four modules. The bypass diode allows current to bypass the shaded module, reducing power loss. Partial shadowing impacts two of the PV string's modules in Figure 2(c). Bypass diodes are employed to mitigate power loss by bypassing the shaded modules.

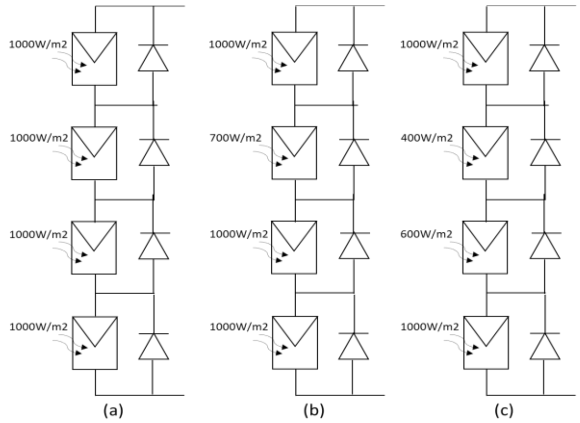

Figure 2: PV Array with and without Shading

Figure 3(a) illustrates the PV curve of a PV array operating without shading, showcasing its optimal performance with a single peak indicating the maximum power output achievable. In Figure 3(b), multiple peaks are observed on the PV curve. The first peak corresponds to the actual peak power output of the array, while subsequent peaks are artifacts caused by partial shading or other factors affecting the array's performance. Figure 3(c) presents the PV curve of the PV array under full shading conditions. Interestingly, the second peak on this curve appears to be higher than the first one. This anomaly suggests a complex interplay of factors such as bypass diode behavior or module configurations, warranting further investigation into the array's response to shading.

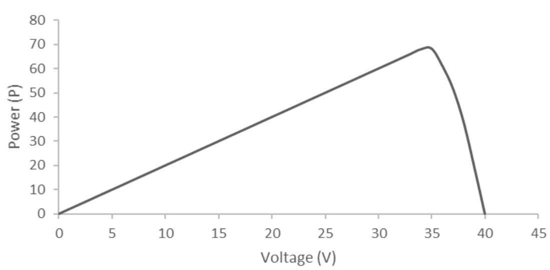

Figure 3(a)

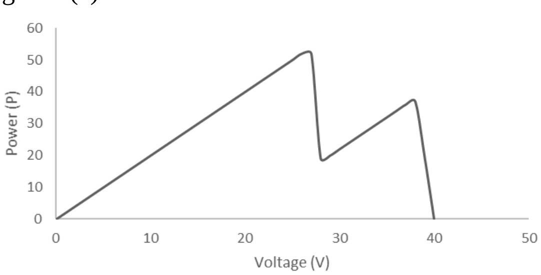

Figure 3(b)

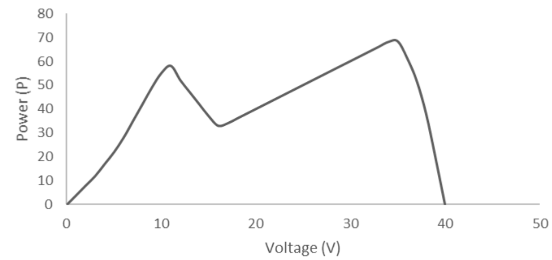

Figure 3(c)

Figure 3: PV Curve under Different Shading Conditions

This shadowing may be caused by a number of things, including surrounding structures, trees, clouds, and even internal shading from equipment on the PV array itself [21]. Understanding the fundamentals of partial shading is crucial for optimizing the performance and efficiency of PV systems, as shading can significantly reduce energy production and affect system reliability. There are several reasons why partial shading occurs:

Obstructions: The solar panels may receive shadows from neighboring structures, trees, or buildings, particularly at specific periods of the day or year when the sun's angle varies [22].

Cloud cover: Clouds can partially shade solar panels, limiting the amount of direct sunlight that reaches the cells even while they spread sunlight [23].

Mismatched Panels: In systems with multiple panels connected in series, if one panel is shaded, it can create a mismatch in the current flowing through the circuit, decreasing the system's overall efficiency [8].

Panel Degradation: Over time, solar panels may degrade due to environmental factors, leading to variances in performance among panels within the same array [24].

A. Challenges Posed by Partial Shading

Partial shading presents several challenges for solar PV systems, including:

Reduced Energy Output: When certain cells or sections of a solar panel are shaded, they generate less electricity, leading to a decrease in overall energy output. This reduction in output can impact the reliability and economic viability of solar PV installations [25].

Hotspot Formation: Partial shading can cause hotspots on shaded cells or panels. Hotspots occur when shaded cells or panels absorb less sunlight, leading to localized heating. Hotspots can cause localized thermal stress, leading to cell or panel degradation, such as microcracks or delamination [26]. These hotspots not only reduce the efficiency of the affected cells but also pose a risk of damage to the panel and the entire system. The temperature rise in these areas can be significant and can potentially damage the affected cells or panels, reducing their efficiency and lifespan [27].

Mismatch Losses: Partial shading on a PV system can lead to mismatch losses, where shaded cells or panels operate at a different voltage or current than unshaded ones. The variance in current and voltage brought on by the darkened cells results in mismatch losses, which lower the system's total power output [8]. This imbalance can lead to a decrease in overall system performance and efficiency.

Potential Module Degradation: Prolonged exposure to PSCs can accelerate the degradation of solar PV modules, reducing their lifespan and increasing maintenance requirements. This degradation may manifest in various forms, such as increased cell corrosion or encapsulant discoloration [28].

Reduced Efficiency: Shaded cells produce less electricity, which reduces the overall efficiency of the solar array [9].

Voltage Drop: Reduced voltage output from shaded cells can have an impact on the system's overall performance, particularly if the panels are linked in series [7].

In conclusion, partial shading can significantly impact the performance of PV systems, leading to mismatch losses, hotspots, and potential damage to modules. Understanding these effects is crucial for optimizing system design and implementing mitigation strategies to minimize the adverse impacts of partial shading [24]

III. MITIGATION STRATEGIES

Significant obstacles to the effectiveness and performance of solar PV technology are presented by partial shade. However, through the implementation of effective mitigation strategies such as bypass diodes, MPPT algorithms, distributed architecture, advanced panel technologies, and optimized system design, these challenges can be overcome. By addressing the complexities of partial shading, the solar industry can continue to advance towards a more sustainable and resilient energy future.

Bypass Diodes: Bypass diodes are incorporated into solar PV modules to reduce the impact of partial shading. These diodes allow current to bypass shaded cells, preventing hotspot formation and minimizing energy losses [4].

MPPT: MPPT algorithms continually modify the operating point of the panels to maximum power output, even in situations when there is partial shadowing. This maximizes the performance of solar PV systems [29].

Distributed Architecture: Distributed architecture designs involve breaking down large solar PV arrays into smaller sub-arrays, each equipped with its own power electronics and MPPT controller. This method reduces the effect of partial shading on the overall functionality of the system [30].

Advanced Panel Technologies: Emerging technologies, such as bifacial solar panels and perovskite solar cells, offer improved performance in partially shaded environments by capturing light from multiple angles and wavelengths [31].

Site Selection and Design Optimization: Proper site selection and system design are crucial for minimizing the effects of partial shading. Techniques such as tilt optimization, row spacing adjustments, and shading analysis tools can help maximize solar exposure and mitigate shading effects [32].

Table-II categorizes mitigation strategies for partial shading in solar PV systems based on shading pattern, severity assessment, and reconfiguration feasibility. It describes dynamic reconfiguration methods, such as MPPT and bypass diodes, for realistic applications. For cases where reconfiguration is not viable, alternative strategies such as module-level power electronics and advanced algorithms are recommended.

Table-II: Classification of mitigation strategies for partial shading in solar PV systems

Shading Pattern	Severity Assessment	Reconfiguration Feasibility	Mitigation Strategy
Uniform	Low, Medium, High	Feasible	Dynamic reconfiguration techniques (e.g., bypass diodes,MPPT) [33].
		Not feasible	Reconfiguration techniques (e.g., module-level power electronics, string-level optimization) [34]
Partial	Low, Medium, High	Feasible	Dynamic reconfiguration techniques (e.g., bypass diodes, MPPT) [33].

		Not feasible	Reconfiguration techniques (e.g., module-level power electronics, string-level optimization) [34]
Intermittent	Low, Medium, High	Feasible	Dynamic reconfiguration techniques (e.g., bypass diodes, MPPT) [33]
		Not feasible	Reconfiguration techniques (e.g., module-level power electronics, string-level optimization) [34]
Persistent	Low, Medium, High	Feasible	Rapid response strategies (e.g., cloud prediction, energy buffering) [23]
		Not feasible	Advanced mitigation techniques (e.g., advanced algorithms, energy storage, alternative system designs) [9]

With respect to the shading pattern, severity evaluation, and reconfiguration feasibility, this table classifies mitigation solutions and offers a concise summary of the many methods for mitigating partial shading impacts in solar PV systems.

IV. CLASSIFICATION OF MITIGATION STRATEGIES FOR PARTIAL SHADING IN PV SYSTEMS

PV systems sometimes encounter partial shadowing, a problem where shadows from surrounding structures, such as trees, buildings, or even clouds, can block sunlight on portions of the PV array. This shading may have an impact on the system's overall performance and drastically lower its energy production. Many mitigation techniques have been developed in response to this problem in order to reduce the effects of shadowing and maximize the efficiency of PV systems. Choosing the appropriate mitigation techniques under PSCs is crucial for optimizing the performance of photovoltaic (PV) systems. The decision-making process involves assessing the shading pattern and the specific requirements of the system, such as response time and complexity of shading. The Figure 3 flowchart illustrates the decision-making process for selecting feasible mitigation techniques for various PSC.

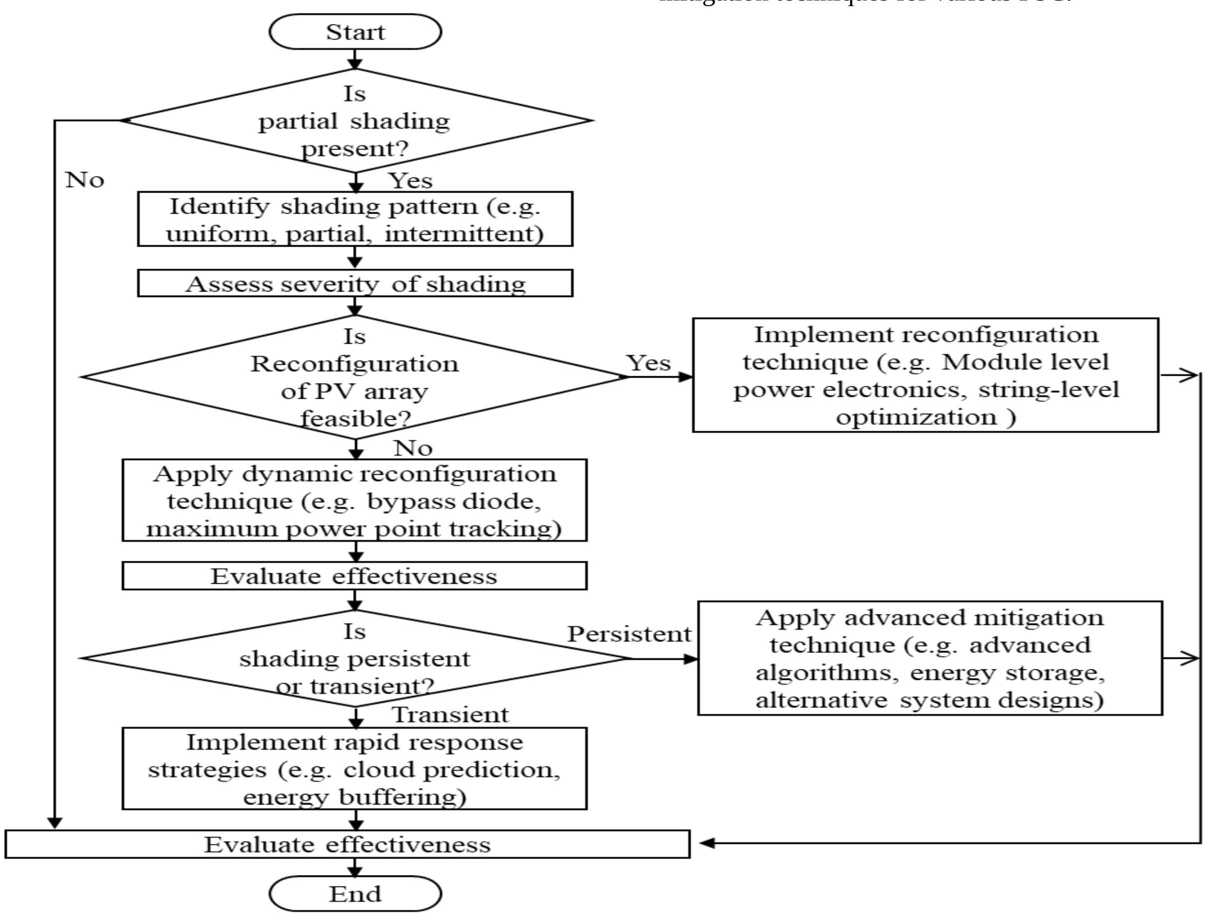

Figure 3: Flowchart for Selecting feasible mitigation techniques under PSCs

Mitigation strategies for partial shading in solar PV systems can be classified into several categories based on their approach to dealing with the challenges posed by shading. Here's a classification:

A. Hardware-Based Solutions

Hardware-based solutions in solar photovoltaic systems encompass a range of technologies aimed at improving efficiency, reliability, and performance. Here's a detailed overview of key components:

Module-Level Power Electronics (MLPE): This approach involves incorporating power optimizers or microinverters at the module level to mitigate shading effects. MLPE refers to a group of technologies designed to enhance the performance and monitoring capabilities of individual solar modules. MLPE devices, such as microinverters and DC optimizers, are installed at the module level to address issues such as shading, mismatch, and partial module failure. Microinverters convert the DC power generated by each solar panel into AC power directly at the panel, eliminating the need for a centralized string inverter. DC optimizers, on the other hand, optimize the DC voltage and current of each panel to ensure maximum power production, while still allowing for centralized inversion. MLPE ensures that each solar panel operates independently, minimizing power loss due to shading on individual panels [34], [35]

Bypass Diodes: Bypass diodes are essential components integrated into solar panels to mitigate the effects of shading or partial module failure. Bypass diodes are integrated into solar panels to create multiple electrical pathways.These pathways provide an alternate path for the flow of current in case a portion of the solar panel becomes shaded or fails, preventing power loss across the entire array. By allowing the current to bypass the shaded or malfunctioning cells, bypass diodes ensure that the unaffected cells can continue generating power efficiently. Bypass diodes are typically installed within each solar panel and are connected in reverse bias across groups of cells. When a portion of the panel is shaded, the diodes allow current to bypass the shaded cells, reducing overall power loss [11], [36], [37].

Smart Tracking Systems: Advanced tracking systems adjust the orientation of solar panels in real-time to maximize sunlight exposure. By dynamically positioning panels, shading effects can be minimized throughout the day [38]. Distributed Maximum Power Point Tracking (DMPPT) is a technique employed to optimize the power output of individual solar panels within an array [39]. Traditional central MPPT systems optimize the entire array based on the weakest panel's performance, which can lead to suboptimal power generation when panels experience varying levels of shading or soiling [3]. Distributed MPPT, on the other hand, involves placing MPPT algorithms or controllers at the panel level, allowing each panel to operate at its maximum power point independently. This approach enables better performance in situations where panels are subject to non-uniform conditions, such as shading from trees or buildings.

Smart Shading Devices: Smart shading devices are innovative solutions designed to minimize the impact of shading on solar panels. These devices utilize various techniques, such as dynamic panel tilting, adjustable louvers, or advanced tracking systems, to optimize sunlight exposure throughout the day. By dynamically adjusting the orientation or shading of solar panels in response to changing environmental conditions, smart shading devices can maximize energy production while minimizing the impact of shading from nearby objects or structures [40].

In summary, hardware-based solutions such as bypass diodes, distributed MPPT, MLPE, and smart shading devices play crucial roles in enhancing the performance, efficiency, and reliability of solar photovoltaic systems by addressing issues such as shading, mismatch, and partial module failure at the panel level.

However, hardware-based solutions along with their advantages have some limitations, and implementation considerations. Bypass diodes introduce a voltage drop, which can slightly reduce the output voltage of the module. Bypass diodes are effective only in scenarios where a portion of the module is shaded or malfunctioning. Placement: Proper placement of bypass diodes across the module is crucial for effective operation. Choosing diodes with appropriate voltage and current ratings is essential for optimal performance. Implementing DMPPT requires sophisticated electronics and algorithms, increasing system complexity and cost. More complex systems may require additional maintenance and monitoring [41], [42]. The Implementation Consideration issue covers Effective communication between individual tracking units is essential for coordinated operation. DMPPT systems should be scalable to accommodate various system sizes and configurations. MLPE systems typically involve higher upfront costs compared to traditional central inverter systems. The reliability of MLPE components may vary, and failures at the module level can be more challenging to diagnose and repair. MLPE components should be compatible with the selected solar panels and overall system design. Proper installation and integration of MLPE components are critical for optimal performance and reliability. Implementing smart shading devices requires additional sensors, actuators, and control algorithms, increasing system complexity and cost. Smart shading systems may require regular maintenance to ensure proper operation and reliability. Smart shading devices should be seamlessly integrated with the solar panel system and overall control infrastructure. Consideration should be given to environmental factors such as wind, snow, and debris, which may affect the operation of smart shading devices [43], [44] In conclusion, each hardware-based solution offers unique advantages and challenges in optimizing solar panel performance. The selection of the most suitable solution depends on factors such as system size, shading conditions, budget, and desired level of control and monitoring.

B. Software-Based Solutions

Software-based mitigation strategies play a crucial role in optimizing the performance and efficiency of various systems, particularly in renewable energy applications like solar power generation. Here's an overview of some key software-based approaches:

Shading Analysis Software: These tools simulate the effects of shading on solar arrays, allowing designers to optimize panel placement and configuration to minimize shading losses [32], [45], [46].

Predictive Algorithms: Utilizing historical data and weather forecasts, predictive algorithms anticipate shading events and adjust system operation accordingly. This proactive approach helps mitigate the impact of shading on PV performance [47], [48].

Remote Monitoring and Control: Monitoring software enables real-time performance tracking of PV systems. Through remote control capabilities, operators can implement adjustments to mitigate shading effects as they occur [49].

Shading Detection Algorithms: Shading can significantly impact the performance of solar panels by causing PSC, leading to mismatch losses and reduced energy output. Shading detection algorithms employ advanced image processing techniques, machine learning algorithms, or sensor data fusion to identify shading patterns on solar arrays. By accurately detecting shading conditions, these algorithms enable effective mitigation strategies, such as panel bypassing, reconfiguration, or tilt adjustment, to minimize the impact on overall system performance [50], [51].

Simulation Tools: Simulation tools are indispensable for assessing the performance and feasibility of solar power systems, especially during the design and planning stages. These tools utilize mathematical models, simulation algorithms, and system parameters to predict system behavior under different operating conditions, including variations in irradiance, temperature, and load profiles. Advanced simulation tools offer comprehensive analysis capabilities, such as energy yield estimation, financial modeling, and optimization algorithms, enabling engineers and designers to evaluate various system configurations, component choices, and control strategies before implementation [50], [51], [52]. By leveraging these software-based approaches, stakeholders in the renewable energy sector can enhance the reliability, efficiency, and profitability of solar power systems, ultimately accelerating the adoption of sustainable energy solutions and contributing to the global transition towards a low-carbon future [53]. The effectiveness of software-based mitigation strategies, such as advanced MPPT algorithms and shading detection algorithms, in mitigating partial shading effects and improving PV system performance can be evaluated through several key metrics and methodologies [54].

Energy Yield Improvement: One of the primary indicators of effectiveness is the improvement in energy yield achieved by implementing these mitigation strategies. By comparing the energy output of PV systems with and without the software-based mitigation techniques under various shading conditions, the impact on overall energy production can be quantified. Simulation tools can be particularly useful in conducting comparative analyses and estimating the potential increase in energy yield.

Advanced MPPT Algorithms: MPPT algorithms are essential in maximizing the energy harvest from solar panels by continuously adjusting the operating point to the maximum power point (MPP) under varying environmental conditions. Advanced MPPT algorithms utilize sophisticated control techniques, such as P&O, INC, and fuzzy logic, to enhance tracking accuracy, reduce oscillations, and improve efficiency. These algorithms leverage real-time data inputs, including voltage, current, and temperature, to dynamically optimize the output power of solar arrays.

MPP Tracking Accuracy: Advanced MPPT algorithms aim to accurately track the maximum power point (MPP) of the PV array, even under PSCs. The effectiveness of these algorithms can be assessed by evaluating their ability to quickly and accurately adjust the operating point in response to changes in irradiance and shading patterns. Performance metrics such as tracking efficiency, settling time, and tracking stability can provide insights into the effectiveness of the MPPT algorithm.

Shading Detection and Response: Shading detection algorithms play a crucial role in identifying shading conditions on the PV array and implementing appropriate mitigation measures. The effectiveness of these algorithms can be evaluated based on their ability to accurately detect shading patterns, differentiate between partial and full shading, and trigger timely responses such as panel bypassing, reconfiguration, or tilt adjustment. Field tests and real-world deployment studies can provide valuable data on the performance of shading detection algorithms in diverse environmental conditions.

System Reliability and Robustness: Another aspect of effectiveness is the overall reliability and robustness of the PV system in the presence of shading. Software-based mitigation strategies should enhance the resilience of the system to shading-induced performance losses and mitigate the risk of hotspots, module degradation, or system downtime. Long-term monitoring and reliability analysis can help assess the impact of mitigation techniques on system reliability and identify any potential weaknesses or failure modes.

Cost-Benefit Analysis: Finally, a comprehensive evaluation should consider the cost-effectiveness of implementing software-based mitigation strategies compared to the potential benefits in terms of energy yield improvement, system performance enhancement, and overall return on investment (ROI). Cost-benefit analysis can help stakeholders make informed decisions regarding the deployment of these strategies and optimize the balance between mitigation effectiveness and implementation costs.

By systematically evaluating these factors, stakeholders can gain a thorough understanding of the effectiveness of software-based mitigation strategies in mitigating partial shading effects and improving the performance of PV systems, ultimately facilitating the development of more reliable, efficient, and economically viable solar energy solutions. Nevertheless, Software-based solutions possess several merits but there are limitations, and implementation considerations. Software-based mitigation strategies, such as antivirus software and intrusion detection systems, provide effective protection against a wide range of threats. However, their effectiveness may vary depending on the quality of the software and the timeliness of updates. Software-based solutions typically have lower upfront costs compared to hardware-based solutions, as they rely on existing infrastructure. However, ongoing maintenance costs, including software updates and license fees, can add up over time. Software-based mitigation strategies are generally easier to implement and maintain compared to hardware-based solutions. They can be deployed relatively quickly and easily across a variety of platforms. Software-based solutions are more scalable than hardware-based solutions, as they can be deployed across large numbers of devices and systems without the need for physical upgrades [41, 43].

C. Hybrid Solutions

Combined MLPE and Software Solutions: Integrating MLPE technologies with advanced software algorithms provides a holistic approach to shading mitigation. By combining hardware-based optimization with intelligent software control, hybrid solutions offer enhanced performance under varying shading conditions [55], [56], [57].

Dynamic System Configuration: Hybrid solutions dynamically reconfigure the system layout based on shading patterns and environmental conditions. By adapting the system in real-time, hybrid approaches ensure optimal performance while minimizing shading-induced losses [5], [58], [59], [60] *Integrated Energy Storage:* Incorporating energy storage systems allows solar PV installations to store excess energy during periods of minimal shading for later use. This buffer capacity helps offset intermittent shading events, ensuring consistent energy production [61], [62], [63]. Optimizing PV system performance in partially shaded conditions often requires a combination of hardware and software approaches. One hybrid solution involves the use of bypass diodes, MPPT algorithms, and shade-tolerant PV modules.

Bypass Diodes: Traditional PV modules are susceptible to significant power losses when shaded, as shading of even a small portion of the module can reduce its overall performance. Bypass diodes are integrated into PV modules to mitigate these losses by providing alternative pathways for current flow around shaded cells.

MPPT Algorithms: MPPT algorithms continuously adjust the operating point of the PV system to maximize power output under varying shading conditions. Advanced MPPT algorithms, such as P&O or incremental conductance, can effectively track the maximum power point even in partially shaded conditions.

Shade-Tolerant PV Modules: Innovative PV module designs, such as interdigitated back contact (IBC) or heterojunction technology, offer improved shade tolerance compared to traditional modules. These modules distribute electrical connections more evenly across the surface, reducing the impact of shading on overall system performance.

Enphase Energy's Microinverter Systems: Enphase Energy pioneered the use of microinverters, which are installed on each individual PV module and incorporate MPPT algorithms at the module level. This distributed architecture allows for optimized power production, even in partially shaded conditions, by mitigating the impact of shading on the entire system.

SolarEdge's Power Optimizers: SolarEdge's power optimizers are DC-DC converters installed at the module level, enabling independent MPPT for each module. By decoupling the modules from the string inverter, power optimizers mitigate the effects of shading and module mismatch, resulting in improved energy harvest.

In conclusion, hybrid solutions combining hardware innovations like bypass diodes and shade-tolerant modules with advanced software algorithms such as MPPT play a crucial role in optimizing PV system performance in partially shaded conditions. Successful implementations and case studies underscore the effectiveness of these hybrid strategies in maximizing energy harvest and improving overall system Reliability. Each category and its subcategories offer distinct approaches to mitigating the impact of partial shading on PV systems. The choice of strategy depends on factors such as system design, budget, and performance requirements.

V. CHALLENGES AND FUTURE DIRECTIONS

Future research could focus on developing integrated MPPT frameworks that combine evolutionary algorithms, reinforcement learning techniques, and dynamic reconfiguration methods to enhance the efficiency, adaptability, and robustness of PV systems under varying environmental conditions. Additionally, experimental validation of these hybrid approaches under real-world PSCs would further validate their effectiveness and practical feasibility. Hybrid optimization framework develops a novel hybrid optimization framework that integrates multiple MPPT algorithms, such as GWO, PSO, MDP, and FP, to achieve synergistic benefits and robust performance in PV systems under PSCs. Performance evaluation and validation with hybrid optimization framework using real-world PV systems under diverse PSCs [64]. Explore the integration of dynamic reconfiguration techniques with advanced MPPT algorithms to enhance the adaptability and responsiveness of PV systems to changing shading conditions [65]. Comprehensive performance evaluations and experimental validations of the hybrid optimization framework using real-world PV systems under diverse PSCs [66].

VI. CONCLUSION

The performance of photovoltaic (PV) systems is significantly impacted by PSCs, which can lead to mismatch losses, hotspots, and reduced efficiency. This review has highlighted the various mitigation strategies developed to address these challenges. Key among these strategies are hardware-based solutions such as bypass diodes and module-level power electronics, as well as advanced software algorithms for maximum power point tracking (MPPT) and dynamic reconfiguration. Additionally, hybrid approaches that combine hardware and software solutions offer promising improvements in system performance under PSCs. The review also underscores the importance of considering practical implementation challenges, including cost-effectiveness, scalability, and compatibility with existing installations. Future research should focus on integrating and enhancing current optimization techniques to further improve the robustness and efficiency of PV systems in partially shaded environments. By addressing these areas, the solar industry can continue to advance towards more sustainable and resilient energy solutions, ensuring that PV systems can reliably contribute to the global energy demand even under challenging conditions. This comprehensive analysis not only provides a roadmap for future research but also offers practical insights for stakeholders looking to optimize PV system performance in real-world settings. Continued innovation and collaboration in this field will be essential for overcoming the complexities of partial shading and maximizing the potential of solar energy.

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