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Fine-Combination-Based Adaptive Reconfiguration for PV Arrays Under Graded Non-Uniform Shading Conditions

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ABSTRACT: Partial shading conditions negatively affect the operation of solar energy systems. In this research, advanced methods were used to reconfigure solar panels to reduce energy losses in photovoltaic (PV) arrays due to unavoidable irregular partial shading caused by clouds, dust, and other factors. To solve this problem, the interconnections between the panels can be dynamically changed to mitigate the negative effects of partial shading. This means that the system can reconfigure the connections so that the panels exposed to more sunlight are connected together, which minimizes energy losses caused by shading. In this paper, we address the electrical mismatch losses caused by traditional hard-threshold-based reconfiguration methods. We introduce a fine-combination adaptive technique that continuously optimizes electrical connections based on real-time shading patterns. The tests under diverse shading conditions show that he proposed technique reduces mismatch losses and improves power extraction by up to 62.5 % validated by experimental tests.

KEYWORDS: Photovoltaic (PV) systems, Partial Shading, Dynamic reconfiguration, Electrical mismatches, Adaptive reconfiguration, Graded shading, Level-aware reconfiguration, System optimization

I. INTRODUCTION

Photovoltaic (PV) system constitutes one of the most promising technologies in realm of renewable energy creation and is usually assembled by chain-gridding together a PV cell in series-parallel structures to satisfy voltage and current demand of usable applications [1]. These systems however have a limited tolerance to environmental changes, and thus highly likely to have their performance reduced by an extreme margin under situations where the environment does not operate consistently, which is partial shading due to moving clouds, buildings and other objects shading a section of the array, preventing sunlight to reach those sections [2]. In addition, as the modules age, further variations in behaviour appear in the modules generating further differences in the performance of the electrical characteristics as well as passing on to the overall energy produced [3]. The effect of partial shading on the PV systems is a broad range of adverse effects. Electrical mismatch between modules can take place when modules are differentially irradiated and the overall power output of the system can be significantly reduced [4],[1]. Such mismatch may also result in hotspots that can degrade parts of the systems with time [2]. To reduce these losses bypass diodes are frequently added, to safeguard shade modules, but this adds numerous crests to the power voltage PV array design and complicates maximum power point tracking (MPPT) [2]. The effects of partial shading cannot be merely in function of the intensity of the partial shading alone but highly dependent upon the topology of the array interconnection. Well known topologies are series-parallel (SP), total-cross-tied (TCT), bridge-linked (BL) and honey-comb (HC) topology [5]. Research has showed that TCT tends to deliver the most effective efficiency in a wide range of partial shading levels with the only hindering aspect being that TCT is vulnerable whenever the shaded cells are situated in the same row [5]. Other environmental effects like fluctuation in irradiance, snow cover, ice and dust deposit further deteriorate array efficiency [6]. Partial shading is one of the most serious technical problems to proper functioning of PV systems. It causes mismatch loses that compel otherwise healthy modules to run at less than optimum efficiency or even not run at all [7],[8]. It also leads to severe losses of power output and is in fact one of the main causes of energy losses in PVs, either through shadows due to buildings or through clearances due to clouds [10]. The issue is not only to reduce power but also the creation of several maximum power points (MPPs), which is why tracking the global MPP becomes too hard [11]. In addition, non-uniform irradiation due to obstacles like dust plans, clouds, or trees bend electrical characteristic curves and weaken MPPT algorithms leading in some cases to MPPTs damage of PV modules [12]. Such condition enhances possible hot spots and faster deterioration of system parts [13]. Despite the fact that TCT tends to provide a higher resulting power at minimum mismatch losses than other systems in case of shading, researchers found that TCT does not ensure output to achieve maximum possible power, which is an ongoing challenge of partial shading [14]. This is widely recognized challenge that the researchers have attempted to mitigate through many implementation strategies with array reconfiguration being one of the best approaches to overcome partial shading problems [10]. Fill factor, power loss percentage and overall performance ratio are frequently used as metrics to determine the performance degradation due to shading on the system performance [10]. Dynamic reconfiguration of PV arrays has been introduced as a novel way to overcome the effect of shading by dynamically reducing connections among modules. Nevertheless, these methods have significant limitations such as the number of switches that are required, as the cost of installation and maintenance of the system greatly rises and contribute to the complexity of the system [15],[16]. They also need shade detection sensor, programmable controllers that make it even more difficult to implement [13],[5]. Another major problem is computing load. The size of the problem array increases, the faster the optimal solutions grow in unfeasible time slots [2],[17]. Even though other scientists have tried to minimize such a burden by the application of algorithms that depend exclusively on the current measurements, in practice, that is difficult to carry out [18]. Scalability also continues to be an issue, as traditional methods relying on bypassing or replacing shaded modules are hard to extend to larger installations [19]. Even with hybrid solutions, such as fixed TCT arrays combined with smaller fully reconfigurable adaptive banks, complex sorting and control algorithms are still required [20]. Furthermore, some dynamic reconfiguration solutions fail to improve power output under specific shading patterns, limiting their universal applicability [15]. The emergence of multiple peaks often remains inevitable even after reconfiguration, leading to continued power losses [21]. These limitations indicate that reconfiguration alone is not a comprehensive solution, underscoring the need for complementary approaches [14]. These constraints have driven researchers beyond conventional irradiance equalization principles toward approaches that also account for voltage effects, seeking globally optimal configurations even under complex shading [2]. The need for solutions that can handle unpredictable, highly variable shading patterns has led to the development of more flexible systems that not only disperse shading impacts but also simplify the Power-Voltage (P-V) curve to facilitate MPPT [21]. Such systems must be implementable at the module level and scalable to arrays of any string count [1], especially since array reconfiguration has attracted significant attention due to its ease of implementation and lower cost relative to alternative mitigation methods [12]. The ultimate goal of advanced reconfiguration approaches is to minimize shading's adverse impacts by strategically reorganizing array electrical connections to position shaded modules optimally according to specific performance criteria [22]. Modern methods have demonstrated tangible improvements, with some reconfiguration techniques achieving power output increases of up to 13.8% under shading conditions [11]. Integration of power electronic solutions with dynamic reconfiguration has further enabled the reduction of multiple peaks into a single global MPP, greatly easing tracking [21]. From a practical standpoint, proposed systems employ efficient switching matrices governed by high-speed control algorithms, allowing thousands of possible module configurations with real-time responsiveness even for large arrays [23]. Trends are also moving toward hybrid solutions that integrate adaptive battery banks with switching matrices and power conditioning systems, achieving power enhancements of up to 20% under full illumination [11]. These guidelines signal the direction that PV systems are likely to take in response to the difficulties of partial shading and environment variability in the future.

II. LITERATURE REVIEW

Electrical mismatches between modules are impeded when modules in series and sometimes in parallel also experience unequal irradiances to cause a high degree of mismatch losses as well as system efficiency greatly diminished [4]. Besides, shaded cells can turn into reverse-biased cells and begin functioning as loads instead of energy producers, which results in the formation of so-called hotspots, which contribute to the acceleration of modules degradation and may result in their permanent damages [14]. Partial shading effects have compelling complexity that has driven the post-factum to conduct rows of studies dedicated to their mitigation strategies which can be generally categorized into two broad categories whose recovery methods are referred to as either static PV array reconfiguration (SPVAR) or dynamic PV array reconfiguration (DPVAR). In SPVAR, reconfiguration of modules physically occurs without changing their electrical interconnections though electrical interconnections of modules are dynamically changed based on real time irradiance data in DPVAR [12],[14]. The two strategies seek the goal of dispersing the shading effects within the array in a more uniform manner losing less power. Nevertheless, they both have different implementation issues and limitations [4]. Dynamic PV array reconfiguration (DPVAR) methods specifically adjust real time electrical interconnections between modules to maximize power output, whilst not physically moving those modules. These methods have a tendency to use principles of irradiance equalization, where like-irradiance modules are kept in the same rows or strings in order to reduce mismatch losses. To estimate the uniformity of irradiance at the array, this concept proposes an equalization index, and ideal configurations aim at minimizing the index [2]. One notable method, Electrical Array Reconfiguration (EAR), forms rows by aggregating modules with similar illumination levels. This requires real-time current and voltage measurements from each module but often involves numerous switches and sophisticated control systems that increase system complexity and cost [4]. Other strategies target SP arrays by reorganizing electrical interconnections to place shaded modules where they have minimal adverse effects, frequently guided by predefined operational priorities [22]. A different technological direction, Switched-Capacitor Differential Power Processing (DPP), employs Active Diffusion Charge Redistribution (ADCR) architecture to enhance energy yields under mismatch scenarios, providing additional voltage boosting when shading is not present. This technique balances power by continuously measuring module voltages and irradiance, then redistributing charge accordingly [24]. Unlike methods relying solely on irradiance equalization, direct power evaluation techniques use mathematical models to directly calculate the maximum output power, framing the reconfiguration as optimization problems such as the 0-1 multi-knapsack formulation to identify the most efficient electrical configurations [14],[2]. Recent advances also include machine learning approaches. Regularized neural networks trained on panel-level sensor data have been utilized to determine optimal array topologies under diverse shading scenarios, achieving simulated power gains up to 11% even when accounting for wiring losses [19]. First, though these dynamic reconfiguration methods have various benefits, there are major implementation challenges. They usually demand wide-scattered networks of sensors, large number of switches that increases the cost of installation and maintenance and intricate regulations algorithms that need to constantly alter with altering irradiance levels [15],[16]. Besides, not all dynamic schemes can improve power generation when under particular shadow patterns, which indicates a fundamental limitation in such methods [15],[16]. Recent researches focused on the development of reconfiguration techniques capable of operating under any shadowing patterns, support module-level reconfiguration, and grow efficiently to variable-length strings [1]. Out of the other possibilities of interconnection, TCT has remained a preferred option because it processes the mismatch losses better than any other form of interconnections, although it remains inappropriate in all circumstances, as it cannot always maximize the output under partial-shading circumstances [5],[14]. Such a simplistic manner of thought brings in significant constraints when faced with the realities of partial shading in the practice of PVs. The majority of these reconfiguration methods are based on the irradiance-equalization rule, which aims at maximizing the occurrence of modules of similar irradiances to be in the same rows or strings to reduce the mismatch impact [2]. Nonetheless, this principle is prone to minimizing the minimum row current without giving much attention to the voltage dynamics so that these schemes do not produce globally optimal configurations in some cases of shadings [2]. Also, the binary classification cannot reflect the continuous range of irradiances presented in real installations. The fact is that PV arrays face the gradients of shading due to the diversified sets of clouds, architectural shadows, trees, and accreted dust. These subtle shading curves produce complex electrical interactions which naive binary approaches cannot resolve so easily. Both static and dynamic reconfiguration approaches based on binary classification are faced with a hard time. Whereas static approaches do not require a broad switching hardware and sensor array, the fixed interconnection topologies make them unadaptable in respect to their responses to environmental variations, thus they do not have the potential to optimally maximize power generation in arbitrary mismatch conditions when taking random defects, failures or non-uniform module aging into consideration [15] [16]. More flexible solutions are dynamic solutions, but they have their limitations. They usually require a lot of switches that highly complicate installation and maintenance costs, as well as complexity of operations [15],[16]. More importantly, certain dynamic solutions do not have the capability of enhancing power generation under certain shadow patterns and this reveals deep-seated weaknesses in how these solutions handle complex shading [15]. Already even the most reliable conventional topologies, like TCT, but still, although one sees a performance gain compared to other static layouts in regards to the mitigation of mismatch, the performance is, nevertheless, lower than what can be achieved in the face of partial shading [14]. All of these observations point to the unnecessity of more advanced strategies that can support the non-stopped nature of shading intensities and abandon the simplistic binary models towards the more comprehensive, optimization-based strategies.

III. PROBLEM FORMULATION

A common issue of dynamic reconfiguration techniques is the unnecessity of more advanced strategies that can support the non-stopped nature of shading intensities and abandon the simplistic binary models towards the more comprehensive, optimization-based strategies. In practice, graded non-uniformity distributions of shading cause different modules to have differing irradiance, and hence they may have differing current and voltage outputs, which complicates power optimization in the end. Consequently, the problem of designing a PV array with traditional reconfiguration technique suffers from electrical mismatch losses caused by binary hard-threshold-based PV panel activity identification methods. In this study, a specific effort is made towards addressing these problems using a set of simulations possibilities in MATLAB /Simulink to simulate and analyze efficient fine reconfiguration schemes. Conventional ways of describing shading tend to be based on the binary scheme of either classifying modules as either shaded or unshaded. Convenient in the design of an algorithm as it might be, such a dichotomy does not accommodate the complexity of shaded graded environments. Partial irradiance modules such as partial brightness may still provide large contribution to overall power and rather often are either improperly classified or poorly trapped in the reconfiguration plans. Such simplification leads to not so optimal reconfiguration results, and a decrease in the system efficiency especially when there are some gradients of shading in the array. The acknowledgment of this weakness highlights the need of more spectroscopic procedures that can model the range of irradiance changes that are observed in actual installations. There is yet another point of critical consideration, which is the electrical effects of incorrect array connections, primarily in parallel systems. When they are configured in parallel, with no concern in matching, when modules having different outputs of current are used the unequal load makes strong modules to be used to make up the weak modules. This is compensation not only reduces the efficiency of the whole system, but may even activate bypass diodes or cause reverse flows, and thereby causing damage to particular modules. Thus, an electrical reconfiguration scheme should be carefully engineered to consider such electrical interactions in order to attract current equalization among parallel-joined modules, to reduce significant mismatch-generated losses. The general goal of the research is to realize a quasi-constant voltage generated across the PV array that is coupled with successful minimization of the shading losses due to mismatched losses. This objective requires flexible reconfigurable interconnections of modules so that the shaded modules can be cleverly grouped to ensure that the present uniformity is maintained in each string or column. This type of strategy assists in flattening the P-V attribute curve effectively reducing the occurrence of multiple power peaks that complicate MPPT. By streamlining the P-V profile, the system becomes more capable of consistently operating at or near its true maximum power point, thereby enhancing energy harvesting efficiency even under challenging, spatially varying shading conditions. Importantly, this approach moves beyond the constraints of binary irradiance models, offering a more robust solution aligned with the complexities observed in practical PV deployments.

IV.PROPOSED LEVEL-AWARE ECONFIGURATION APPROACH

The proposed system models a Fine PV Array Reconfiguration Algorithm that dynamically adapts the connection of PV modules to maximize output under varying configurations. The system considers two key connection topologies, series and parallel, and evaluates the output performance of each combination of two PV sources. Let the maximum PV module value be denoted as PVmax, and a threshold value θ=PVmax/2 is defined to guide the connection logic in the binary hard-thresholding baseline method. Two PV modules, PV1 and PV2, are considered at a time, with output voltage values ranging from 1 to PVmax. The tested connection strategies are as follows:

1-**Conventional Parallel and Series Configurations:**

The Parallel Output Voltage (Vp):

$$Vp=\max(PV1, PV2) \tag{1}$$

The Series Output Voltage (Vs):

$$Vs=PV1+PV2 \tag{2}$$

2.Proposed Fine Combination Strategy:

The system evaluates both configurations and selects the one that yields an output voltage closest to the target PVmax, minimizing deviation:

- Series Deviation:

$$ds=|PV1+PV2-PVmax| \tag{3}$$

- Parallel Deviation:

$$dp=|\max(PV1,PV2)-PVmax| \tag{4}$$

The final output voltage Vo is chosen based on the minimum deviation:

$$\boldsymbol{Vo} = \begin{cases} \mathbf{PV1+PV2}, & \textbf{if ds} < \textbf{dp} \\ \mathbf{\max(PV1,PV2)}, & \textbf{otherwise} \end{cases} \tag{5}$$

3. Conventional 4-Case Method:

A threshold-based decision-making logic is used for comparative analysis:

$$\boldsymbol{Vm} = \begin{cases} \mathbf{\max(PV1,PV2)}, & \textbf{if } \mathbf{PV1 > \theta \wedge PV2 > \theta} \\ \mathbf{PV1}, & \textbf{if } \mathbf{PV1 > \theta \wedge PV2 < \theta} \\ \mathbf{PV2}, & \textbf{if } \mathbf{PV1 < \theta \wedge PV2 > \theta} \\ \mathbf{PV1+PV2}, & \textbf{if } \mathbf{PV1 < \theta \wedge PV2 < \theta} \end{cases} \tag{6}$$

All possible combinations of PV1 and PV2 in the defined range are evaluated. For each configuration, the proposed method and conventional method outputs are compared. The mean values of the output voltages across all configurations are computed to assess the performance advantage of the proposed fine combination method in terms of output optimization.

V. SIMULATION AND RESULTS

The performance of the proposed fine-reconfiguration technique has been evaluated by conducting a simulation study in MATLAB. To model the activity two PV modules at different irradiance settings, a dedicated script was created that sequentially changed the voltage of each module between 1 V and 4 V with two modules, resulting in a combination of 16 different irradiance conditions. This comprehensive sampling has sampled every possible combination and in essence duplicated conditions of uniform, partially shaded, and highly uneven irradiance which are common in practice in PV systems. With every combination of module voltages, four different connection strategies have been tested, namely traditional parallel and series connection schemes, a traditional threshold-based strategy based on fixed logic and the suggested level-slack method based on adaptability. The adaptive approach was used to dynamically switch between series and parallel connectivity, by calculating the absolute difference between each configuration and a set target 4V voltage, and always returned to the connection that reduced this difference the lowest. Table 1 shows the separate voltages of PV1 and PV2 and the resulting output voltages with each strategy with their respective deviations against the target. and a side-by-side comparison of the difference in effectiveness of the hard-threshold-based method verses the proposed adaptive algorithm. The better operation of the proposed adaptive strategy that was observed by conducting this systematic assessment relied on the fact that the output voltage can be projected to meet the target, that is, to minimize the electrical mismatches and consequently improve the effectiveness and output stability up to 62.5%.

Table 1. Output voltage of tested systems under different shading patterns.

Shading case	Output voltage (V)						Deviation from PVmax (V)			
	PV1	PV2	Parallel	Series	Binary Thr.	Proposed Adaptive	Parallel	Series	Binary Thr.	Proposed Adaptive
1	1	1	1	2	2	2	-3	-2	-2	-2
2	1	2	2	3	3	3	-2	-1	-1	-1
3	1	3	3	4	3	4	-1	0	-1	0
4	1	4	4	5	4	4	0	1	0	0
5	2	1	2	3	3	3	-2	-1	-1	-1
6	2	2	2	4	4	4	-2	0	0	0
7	2	3	3	5	3	3	-1	1	-1	-1
8	2	4	4	6	4	4	0	2	0	0
9	3	1	3	4	3	4	-1	0	-1	0
10	3	2	3	5	3	3	-1	1	-1	-1
11	3	3	3	6	3	3	-1	2	-1	-1
12	3	4	4	7	4	4	0	3	0	0
13	4	1	4	5	4	4	0	1	0	0
14	4	2	4	6	4	4	0	2	0	0
15	4	3	4	7	4	4	0	3	0	0
16	4	4	4	8	4	4	0	4	0	0

Figure 1 shows how the proposed adaptive algorithm had voltages that were nearer to the ideal reference in comparison to the traditional approach. The obtained curves illustrate clearly that the hard-threshold-based approach exhibits observable oscillations, regular pairing of voltages far much beyond the ideal operating voltage. Such instability exists because of the fixed form of the decision rules not considering minor differences in outputs of modules. In contrast, the adaptive approach maintains a smoother trajectory that consistently stays closer to the 4 V target, as shown in Figure 1. This improved voltage stability directly contributes to enhanced energy conversion efficiency, reduced electrical stress on system components, and overall longer system lifespan. Figure 1. Comparison of output voltage between the traditional threshold-based method (red curve) and the proposed adaptive method (blue curve) across different voltage scenarios, highlighting superior stability and reduced deviation under the adaptive strategy.

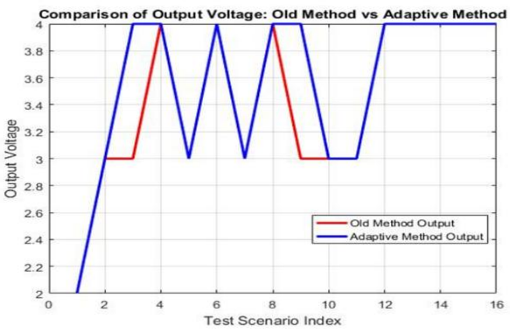

Figure 1. Comparison of output voltage

To validate the simulation results, practical implementation of the proposed adaptive algorithm was conducted. With this scheme, voltage sensors are incorporated to continuously sample the voltage outputs of every PV module, inputting real-time information to microcontroller which performs identical level-sensitive decision logic developed using the MATLAB platform. With such measurements the microcontroller dynamically switches on devices, which are often relays or MOSFETs, to connect up in series or parallel, whichever offers the lowest deviation to the desired, or aspired to, voltage. Such an operation reconfiguration provides the PV system to be operated in real time. under the most favorable conditions, it automatically adapts to variations in shading, partial faults or variations in irradiance. This schematic shows that the simulation in the practice is feasible by providing a direct hardware implementation of the simulation framework, such that the intelligent adaptive design of a PV system is deployed, that can electrically perform optimally in practically all and demanding environmental conditions. Figure 2. Level-aware adaptive PV connection proposed circuit schematic with voltage sensing and decision logic implemented on the microcontroller with switching components to switch between the series and the parallel circuit to achieve the best combination.

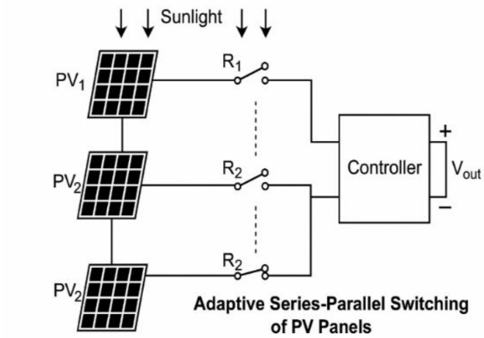

Figure 2. Level-aware adaptive PV connection

VI. DISCUSSION

Simulation results clearly demonstrate that the adaptive algorithm consistently yields output voltages with smaller deviations from the target compared to traditional methods. By continuously evaluating the absolute differences and selecting the optimal connection scheme, the system effectively maintains the output voltage near the desired level, even under varying irradiance and shading conditions. This adaptability enhances voltage stability and ensures more reliable power delivery, which is critical for maximizing energy harvesting and safeguarding downstream electrical components from stress. The comparative study shows how effective is this adaptive reconfiguration mechanism compared to the conventional binary-form-based mechanisms of reconfiguration. The traditional techniques are generally done using fixed threshold logic where PV modules are wired in series or parallel by having very naive thought of comparing the module voltages to some fixed value of reference. Such methods are easy to apply, though they may not realize the smaller differences in voltage, being in effect a sub-optimum switch decision, which can affect the efficiency of the systems, and cause mechanical or heat stress to vulnerable components. The possibility to improve the voltage stability and minimize the fluctuations caused by the mismatched PV modules can be recognized as one of the strongest signs of the efficiency of the proposed method. Voltage stability close to the reference point is critical in providing efficient power conversion and preventing coarse destruction of electronic components which may be very sensitive. The rigidity of the traditional binary methods also leads to observable voltage fluctuations because of the strict nature of the decision rules, which causes fans and oscillations that have a deleterious effect on the overall performance and contributes to energy lost. In contrast, the suggested adaptive approach results in a smoother voltage output because of a less ordinate method of selection: using a dynamic selection mechanism that actively selects which configuration is most suitable to achieve minimal deviation to the target. The enhanced stability leads directly to the increased total power yield because less is lost as suboptimal reconfiguration and effective performance is achieved even in situations of uneven illumination.

Moreover, the controlled voltage levels relieve the voltage regulators and other related electronic components whose maintenance becomes easier and allows the system to last longer. In addition to jointly improving voltage stability, the new level-aware model helps avoid electrical mismatch, i.e. a widespread PV system problem, where non-uniform irradiance, partial shading, or long-term module degradation cause the electrical power level in one module to differ relatively to the other. Power losses, heat buildup and fast aging of parts are things that commonly cause by electrical incompatibilities. The adaptive algorithm reduces the internal voltage differences between connected modules by measuring the compatibilities between modules outputs before determining the connection mode. Such balance contributes to the increased overall reliability and sustainability of the system as well as its accordance to practical requirements of adaptive solar energy systems which should be able to react to the constantly changing environmental conditions.

In spite of these encouraging findings, there are also some shortcomings of the existing model that should be measured. The current model can only be implemented when there are specifically two PV modules and only accepts the decision-making criteria which involve voltage, and lacked any operating parameters incorporating data that considers current, real power, or even changes in the nature of the environment. In addition, the model is based on the assumption that the two panels are always in service and stable conditions and therefore, this reduces its application in the dynamic field environment where one or both panels may fail or subjected to some temporary shading.

VII. CONCLUSION

This study introduced a level-aware reconfiguration strategy for PV panels that adaptively determines whether modules should be connected in series or parallel based on which configuration yields an output voltage closest to a predefined target. Through rigorous simulation and comparison with conventional threshold-based binary approaches, the proposed method demonstrated substantial improvements in voltage regulation. The adaptive mechanism consistently achieved output values nearer to the desired reference voltage, effectively minimizing electrical mismatches and enhancing the overall performance of the system. Furthermore, the proposed strategy keeps the voltage levels near to a perfect reference thereby alleviates some electrical stresses on the important system components and some of the adverse impacts that have always accompanied module mismatch. The development enhances a better and stable PV system that can be stable across various temperature conditions and other environmental changes leading to different loads in efficiencies. Although the results of this work are quite encouraging, they also help to identify several paths to be taken in order to improve and extend this future research. Another notable path will be actualizing this voltage focused reconfiguration methodology into MPPT algorithm. Together with connection optimization may allow the system to change simultaneously its topology as well as operating point, reaching maximum efficiency, under a real-time scenario. The other interesting option is artificial intelligence (AI) and machine learning integration that would boost the decision-making process. More sensitive schemes based on reconfiguration could be induced through the use of more advanced algorithms e.g., genetic algorithms, reinforcement learning frameworks, or fuzzy logic controllers that were capable of synthesizing a more extensive set of parameters such as irradiance.

REFERENCES

1. Mohamed, A., et al. (2018). Advanced PV reconfiguration strategies for shading conditions. Energy Conversion and Management, 174, 331-343.
2. Zhu, Y., Zhao, J., & Li, X. (2020). Reconfiguration techniques for photovoltaic arrays under partial shading conditions. IEEE Transactions on Sustainable Energy, 11(4), 2426-2437.
3. Nahidan, A., et al. (2021). Performance analysis of PV arrays under non-uniform irradiation using improved models. Solar Energy, 221, 245-259.
4. Ameen, M., et al. (2023). Review of PV array interconnection and shading resilience. Renewable and Sustainable Energy Reviews, 155, 111918.
5. Vadivel, T., et al. (2021). MPPT optimization under partial shading. IEEE Access, 9, 14792-14804.
6. Mallick, P. S., et al. (2024). Novel hybrid reconfiguration for enhanced PV performance. Solar Energy, 274, 427-439.

7. Bonkoungou, D. C., et al. (2022). Comparison of PV array configurations under shading patterns. Energy Reports, 8, 219-229.
8. Liu, W., Liu, Y., & Hu, S. (2019). Novel PV array configurations to enhance partial shading tolerance. Renewable Energy, 138, 1056-1069.
9. Vicente, F., et al. (2015). Optimal reorganization of PV arrays. Solar Energy, 117, 89-101.
10. Niazi, K. H., et al. (2021). Switched-Capacitor Differential Power Processing for PV systems under partial shading. IEEE Transactions on Power Electronics, 36(8), 8991-9004.
11. Narayanaswamy, R., et al. (2023). Scalability issues in dynamic PV configurations. Solar Energy Materials and Solar Cells, 247, 111974.
12. Fang, Y., et al. (2022). Hardware complexities in dynamic PV reconfiguration. IEEE Transactions on Power Electronics, 37(5), 5432-5443.
13. Fang, Y., et al. (2022). Efficient switching schemes for PV arrays. IEEE Access, 10, 21987-21999.
14. Hamad, D. A., et al. (2024). Hotspot formation under partial shading and mitigation. Renewable Energy, 200, 1095-1106.
15. Durango-Flórez, J., et al. (2022). Quantifying partial shading impacts on PV arrays. Renewable Energy, 180, 470-482.
16. Udenze, C. O., Kamanyi, J. R., & Umenne, P. (2018). Impact of aging on PV module performance under non-uniform conditions. International Journal of Energy Research, 42(14), 4332-4344.
17. Srinivasan, R., et al. (2021). Mismatch effects in photovoltaic modules and arrays. Renewable Energy, 164, 88-98.
18. Nguyen-Duc, C., et al. (2022). Mitigation of mismatch losses in PV systems. IEEE Access, 10, 5893-5904.
19. Romano, P., et al. (2013). Fast control algorithms for PV arrays. IEEE Transactions on Industrial Electronics, 60(4), 1400-1411.
20. Bastidas-Rodríguez, J. D., et al. (2022). Real-time optimization of PV arrays. International Journal of Energy Research, 46(4), 5329-5343.
21. Cherukuri, R., et al. (2021). Current-based algorithms for PV array reconfiguration. Solar Energy, 220, 44-56.
22. Kadhim, S. H., et al. (2024). Effects of environmental factors on PV systems: A review. Renewable and Sustainable Energy Reviews, 172, 113110.
23. Varma, V. R., et al. (2021). Investigation of shading effects on PV array performance. Solar Energy Materials and Solar Cells, 229, 111149.
24. Niazi, K. H., et al. (2021). Switched-Capacitor Differential Power Processing for PV systems under partial shading. IEEE Transactions on Power Electronics, 36(8), 8991-9004.