Comparative analysis of various reconfiguration strategies of PV array in partial shading conditions: a review

Vaishali Gautam[a], Shahida Khatoon[a], Mohd Faisal Jalil[b] and R. C. Bansal[c,d]

[a]Department of Electrical Engineering, Jamia Millia Islamia, New Delhi, India; [b]Department of Electrical Engineering, Aligarh Muslim University, Aligarh, India; [c]Department of Electrical Engineering, University of Sharjah, Sharjah, UAE; [d]Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa

ABSTRACT

Photovoltaic system performance depends on factors like bypass diode topology, array size, arrangement, and shading intensity. Partial shading causes mismatch losses and reduced power production. Though many methods address this, they may not fully optimize power. Reconfiguring PV modules offers a promising solution to minimize power loss. In this paper, major Static and Dynamic reconfiguration strategies have been discussed. The methodology, benefits, and limitations of each approach are compared and evaluated. The research set out to compare and contrast the effectiveness of static and dynamic reconfiguration approaches with regards to energy output, shading losses, and mismatch losses. The results showed that dynamic reconfiguration was more effective in reducing shading losses and increasing energy yield compared to static reconfiguration. This article aims to help researchers and readers in gaining an understanding of the available reconfiguration strategies and factors that affect their selection. Overall, this article is a valuable resource for researchers, engineers, and professionals working in the field of renewable energy, particularly in the area of PV systems.

KEYWORDS
Photovoltaic (PV) modules; PV systems; partial shading; PV array; reconfiguration strategies

1. Introduction

A global trend towards renewable energy options, including solar power, has been triggered by the rising depletion of non-renewable energy sources [1]. Photovoltaic systems are highly preferred since they have minimal ecological consequences and are adaptable to various applications. Partial shade can greatly impede the efficiency of PV arrays by causing mismatch losses between the maximum power output of the array and its individual modules [2,3]. It is essential to address these losses caused by mismatches in order to optimize the energy output of photovoltaic (PV) systems [4,5]. Array reconfiguration is a crucial approach to reduce these losses by changing the placements of modules that are in the shade and those that are not [6,7]. Several techniques, such as Series-Parallel (SP), Total Cross Tied (TCT), and Bridge Linked (BL), have been suggested to enhance performance in situations with partial shading [8–12].

The two main categories of reconfiguration schemes are dynamic reconfiguration and static reconfiguration. Figure 1 depicts the advantages and disadvantages of PV reconfiguration strategies. Static reconfigurations use a fixed connectivity structure to increase power output in the presence of partial shade. Since these shading scenarios do not dynamically alter the module's placement, it is always in the same place. In other words, it can be considered as a fixed or permanent arrangement.

The researchers [13] propose the incorporation of an additional region called SuDoKu (EXRSDK) architecture to enhance the performance of solar arrays in the presence of genuine fractional partial shadowing. The EXRSDK enhances efficiency, fill-factor, global maximum power point (5733.0 W), and minimizes mismatch power loss (721.0 W). Simulations and testing validate its higher performance compared to conventional configurations such as total cross-tied and SuDoKu. An EXRSDK array with dimensions of 9×9 generates an annual income of ₹212,370.87. The EXRSDK is a financially viable solution that does not require any extra parts and shows substantial enhancements in realistic shading situations. Researchers [14] have come up with the optimized SuDoKu (OPSDK) method for rearranging photovoltaic arrays to lessen the effects of partial shading and cut down online losses. MATLAB/Simulink simulations show that OPSDK works better than five advanced designs, cutting wire length by up to 37.98% and mismatch power losses by 643.1 W. The OPSDK method makes the most money and energy

CONTACT Mohd Faisal Jalil mfaisaljalil@gmail.com Department of Electrical Engineering, Aligarh Muslim University, Aligarh, Uttar Pradesh 202002, India; R. C. Bansal rcbansal@ieee.org Department of Electrical Engineering, University of Sharjah, Sharjah, UAE

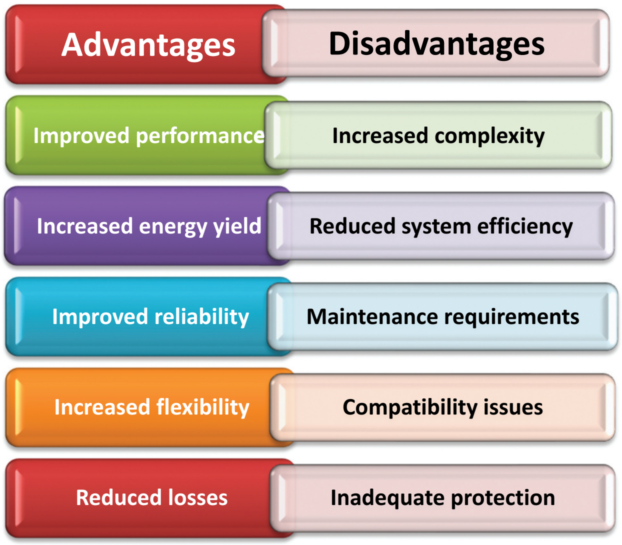


Figure 1. Advantages and disadvantages of PV reconfiguration strategies.

each day (₹154,003.72) of all the configurations that were tried. This in-depth study shows that OPSDK is good at increasing power output, lowering losses, and making more money, which makes it a long-lasting and perfect choice for changing the layout of PV arrays. Under passing cloud conditions, a pattern that relies on the SuDoKu puzzle is suggested in [15] for changing the module's physical positions. Different PV array layouts, including Series-Parallel (SP), Bridge-Linked (BL), Honey-Comb (HC), Total Cross Tied (TCT), and Ladder, have been using this pattern arrangement. Reference [16] presents an analogous pattern layout to spread shading effects. This design is offered in ref [17]. as a variation. Ref [18]. suggested non-symmetrical patterns and hybrid PV array topologies to distribute shade impacts. A new physical PV array concept is provided later, in [19]. The main objective of this arrangement is to increase the gap between neighbouring photovoltaic modules in the array. Researchers [20] presented and evaluated the Dominant Square puzzle technique, a novel puzzle-based reconfiguration scheme. The standard Total Cross Tied (TCT) interconnection's PV modules are configured using the proposed dominance square approach. Competence Square (CS) technology was also introduced by the authors for physically rearranging PV panels in a TCT connectivity architecture. In [21], an optimal pattern utilizing the Latin square pattern to distribute the shade uniformly throughout the array and minimize mismatch loss, all while keeping the total cross-tied electrical connection intact is proposed. Researchers [22] suggests a Two-Step Optimal PV Array Reconfiguration. This process consists of two steps. The author proposed a technique called SD-PAR, which involves physically relocating the PV array to disperse shading and increase power generation under partial shading conditions [23]. To mitigate the damaging effects of shadowing on a PV array, the authors of Reference [24] developed an effective SuDoKu configuration, which, when compared to TCT and SuDoKu PV arrays, results in a global maximum power increase of 7.03% and 5.2%, respectively. Ref [25]. offers a description of the algorithm for settled electrical reconfiguration. The research reveals that the PV array utilizing SER technology exhibits the highest output power, improved efficiency, and fill factor in all scenarios when considering shading patterns.

A non-symmetrical reconfiguration strategy with PV module relocation is suggested in the article [18]. The implementation of non-symmetrical reconfiguration strategies, as proposed in [26], has been discovered to boost electricity output and improve efficiency in partial shading conditions (PSC). To further enhance power generation, a two-phase array reconfiguration method (TPAR) has been developed, as described in the same article. Additionally, reference [27] suggests a static reconfiguration of neighboring modules (SRAM). The modules that actually belonged to a ROW are separated by SRAM with the least amount of space. The superiority of SRAM over TCT in FF was confirmed by a comparison test. 'Odd-Even-Prime' (OEP) configuration, a novel static one-time reconfiguration was presented [28]. The OEP layout efficiently distributes the shade over all potential rows, which reduces the power loss caused by PSC and prevents repeated peaks in p-V characteristics. To reduce the number of MPPs at the local level and do away with the requirement for a complicated algorithm to find the MPP at the global level, a ken-ken puzzle-inspired reconfiguration strategy is proposed [29]. Reference [12] employs two highly effective chaotic techniques, namely Arnold's Cat Map and Henon Map, to reconfigure the PV array. The proposed chaotic map-based techniques, ACM and HMACM, consistently outperform existing configurations under all shading conditions.

According to the type of shade, dynamic reconfiguration-based systems change the position of modules in an array, redesigning the array dynamically to increase power output. To put these designs into practice, switches, sensors, and controls are needed. Ref [30]. presents an equalisation index (EI)-based optimization technique. The primary goal of this method is to lessen mismatch loss by making each ROW's PV modules get the same amount of irradiance through the use of electrical switches. A perfect method for reconfiguration is proposed to decrease the Irradiance Mismatch Index (IMI) [31]. To design this optimal problem, the Mixed Integer Quadratic Programming (MIQP) technique is employed, and the branch and bound algorithm is utilized to solve it. For recurring shadowed situations, a dynamic PV (DPV) array technique was put out in [32]. In this method, the suggested algorithm receives three inputs: a PV array voltage profile, a current profile, and an irradiance profile. The solution that can be reconfigured is optimized, and signals are sent to the switches based on that optimization. In [33], a reconfiguration strategy that is self-adaptive employing a fuzzy logic controller was created. The controller searches for the optimal arrangement when the voltage of the first row drops below a certain threshold value. The technique of adaptive bank of solar cell array has been extended to module PV arrays and reported [22,34]. This method incorporates the use of an ANN to regulate the switching matrix. In addition, in [22], a scanning method was devised that makes use of the current variation index (CVI).

To satisfy the 24 V load requirement, a dynamic reconfiguration technique has been proposed [35] for linking PV modules into two groups at the same time. Modules that are darkened, filthy, or broken can be pinpointed with the help of the fuzzy controller and fitting tool estimator in this method. A unique PV reconfiguration design, proposed by Ramasamy and coworkers, keeps the output current constant for the desired demand [36]. In [37], the issue of irradiance equalization control is discussed, where the mean irradiance of the PV array does not equal the sum of the irradiance of each row. To mitigate the impact of non-uniform spatial irradiance profiles on real-time PV power generation, a dynamic reconfiguration approach was presented [38]. A flexible switching matrix-based elastic photovoltaic structure (EPVS) was proposed [39]. The PV modules are connected to the other modules using this switching matrix either in series or parallel. A strategy is presented that involves joining numerous strings including substrings of similar power levels using a DC/DC converter [40]. A DC/DC converter connects all the strings, which then converge on a single DC bus. Similar methodology is described [41]. This method was used to develop an optimal switching set (SWS) topology for PV modules. Additionally, a new water-pumping system based on a reconfigurable PV array was introduced [42]. In [43], an adjustable framework with fixed components was designed. To bridge the gap between the flexible and rigid parts, this method makes use of the established irradiance measurement for each string. A novel Automatic Reconfiguration System based on Rough Set Theory (RST) for SP topology is presented [44]. In addition, a novel genetic-algorithm-based reconfiguration method is presented [45], which aims to link PV modules on each string that have the closest irradiance values. For PV modules that are not uniformly aged, a distinct reconfiguration strategy is proposed [46]. Bypass diodes are used to connect several solar cells in series to create the reconfiguration. An improved reconfiguration topology is later put out to minimise mismatch effects [47]. The SPICE circuit simulator, which uses this topology, can forecast the ideal configuration for unpredictable operating circumstances.

This article summarizes the static and dynamic solutions presented in the published literature to increase the maximum power production of a PV system under partial shade conditions, along with an analysis of the benefits and drawbacks of each. The review focuses on two main categories of PV reconfiguration, namely Static and Dynamic reconfiguration, and examines and compares the major strategies used in each of these methods. Section 2 covers the topic of partial shading conditions, while Section 3 focuses on various reconfiguration strategies found in the literature. Section 4 presents the results and discussion. Figure 2 illustrates the structure of this paper.

2. Partial shading condition (PSC)

It is common practice to link PV cells in series and in parallel to maximize the voltage and current output of the PV module [48]. By connecting PV modules in series and parallel, a PV array can be created. However, due to various factors such as passing clouds, dust, or shadows of surrounding structures, uneven irradiance is a common issue in PV arrays that have large surface areas. This occurrence is referred to as

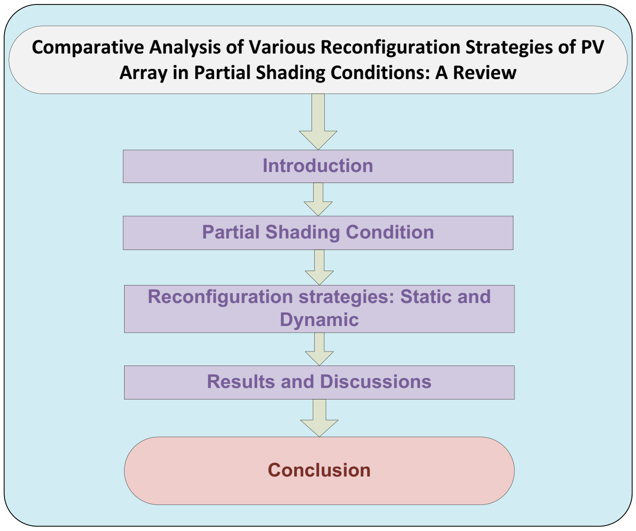


Figure 2. Structure of this paper.

partial shading condition (PSC). In PSC, shaded PV modules provide a lower photo-generated current than their un-shaded counterparts.

So, this PV module that is shadowed is pushed to produce large current in order to match the current in the string. This makes the shaded PV module act like a load and use the power that other cells produce. The temperature of the PV modules that are shaded continues to rise as a result of the thermal effect of resistance. Because of this, the PV panel may overheat and fail. To prevent hot spot effects, bypass diodes can be connected in reverse to PV modules. When the bypass diodes are reverse biased, they provide a short circuit path for the shaded PV cells [49–52]. But when bypass diodes are turned on, they create multiple peaks on the output power curve. This makes it difficult for Maximum Power Point Tracking (MPPT) algorithms to find the Global Maximum Power Point (GMPP) of a PV system. Figure 3(a-d) shows the 4 most common ways of a typical shadow. On comparative analysis various type of PV arrays, the researchers have considered the following patterns of shade: Long Narrow (LN), Short Narrow (SN), Long Wide (LW), and Short Wide (SW). The number of shaded columns (width) and the number of shaded modules per column (length) are used to define the shading conditions.

Long Narrow (LN) refers to a configuration where the solar panels are long in length and narrow in width. This configuration is often used in areas where the sun is strongest in the morning or early afternoon. Figure 3(a) shows LN shading pattern.

Short Narrow (SN) refers to a configuration where the solar panels are short in length and narrow in width. This configuration is often used in areas where there is limited space for the PV array and where the sun is strongest in the morning or early afternoon. Figure 3(b) illustrates SN shading pattern.

Long Wide (LW) refers to a configuration where the solar panels are long in length and wide in width. This configuration is often used in areas where the sun is strongest in the afternoon or evening. Figure 3(c) demonstrates LW shading pattern.

Short Wide (SW) refers to a configuration where the solar panels are short in length and wide in width. This configuration is often used in areas where there is limited space for the PV array and where the sun is strongest in the afternoon or evening. Figure 3(d) indicates SW shading pattern.

3. Reconfiguration strategies

When a PV array is partially shaded, there is a significant difference between the actual power output and the maximum power that could be obtained at that time. However, the PV array's MPP and V-P properties can be enhanced to lessen this disparity. In order to optimize the array for the present irradiance levels, it may be necessary to make changes to the interconnection method, the number of panels linked in series and/or parallel, or the location of the shaded panels within the array. By clustering panels according to shadow intensity to prevent mismatch and by adjusting the no. of panels in series or parallel to balance row current, the interconnection design may be dynamically updated to create more electricity. The power losses associated due to partial shading conditions are reduced by PV array reconfiguration [53–55].

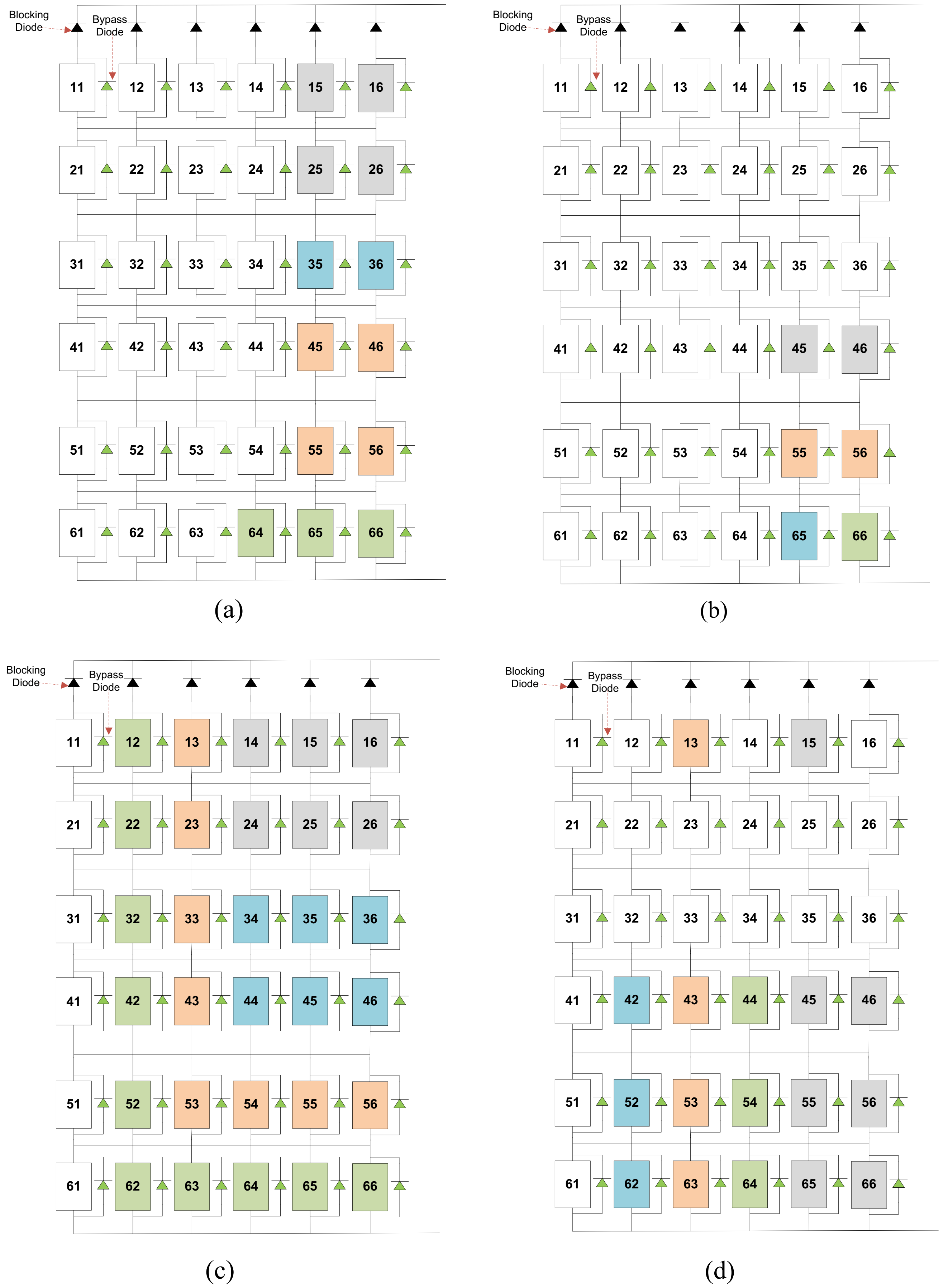


Figure 3. Shading patterns, (a) long and narrow shading pattern, (b) short and narrow shading pattern, (c) long and wide shading pattern, (d) short and wide shading pattern.

The various approaches to determining the optimum ideal configuration are covered in this section and can be divided into two groups: static reconfigurations and dynamic reconfigurations. Static and dynamic PV array reconfiguration are two techniques used to optimize the performance of a photovoltaic (PV) system by rearranging the electrical connections between the individual solar panels. The frequency and approach to reconfiguration is where the two approaches diverge.

Static reconfiguration involves rearranging the connections between panels once, usually during the installation process, and leaving the connections unchanged thereafter. The aforementioned solution is relatively uncomplicated and direct, leading to enhanced energy production and dependability. However, its ability to entirely optimize performance in accordance with varying environmental circumstances may be limited. Dynamic reconfiguration, on the other hand, involves actively monitoring and rearranging the connections between panels in real-time, based on changing environmental conditions such as shading or changes in the direction of the sun. This allows for continuous optimization of performance and increased energy yield, but requires specialized equipment and technical expertise, and may result in increased costs and maintenance requirements. The final decision between static and dynamic reconfiguration should be based on the unique needs of each PV system, as well as the objectives of the owner or operator. It is important to carefully consider the advantages and disadvantages of each technique before deciding on a reconfiguration strategy. Figure 4 shows classification of PV array reconfiguration technique.

3.1. Static reconfiguration

The static reconfiguration technique systematically designs the physical placement of a module inside the array so that the shade effect is disseminated almost evenly throughout the array. The positioning of panels in a PV array can be achieved using various methods such as using puzzle patterns like Su Do Ku, Futoshiki, and magic square patterns, or employing suitable positioning algorithms. After that, the connectivity is complete and unchanged. This approach simplifies the complexity of installation and control by not utilizing switches or other extra circuits [56].

Due to the absence of switching devices, this method is typically more practical and less expensive to implement. In order to physically alter the PV modules using static methods, skilled individuals are needed, and the usage of long cables results in significant power losses. The static techniques can only be used in PV array structures with a minimal footprint. Techniques for static reconfiguration don’t need sensors and can save a lot of switches. However, because the interconnection scheme is fixed, they are unable to adaptively determine the best interconnection scheme when the irradiance conditions change [57,58].

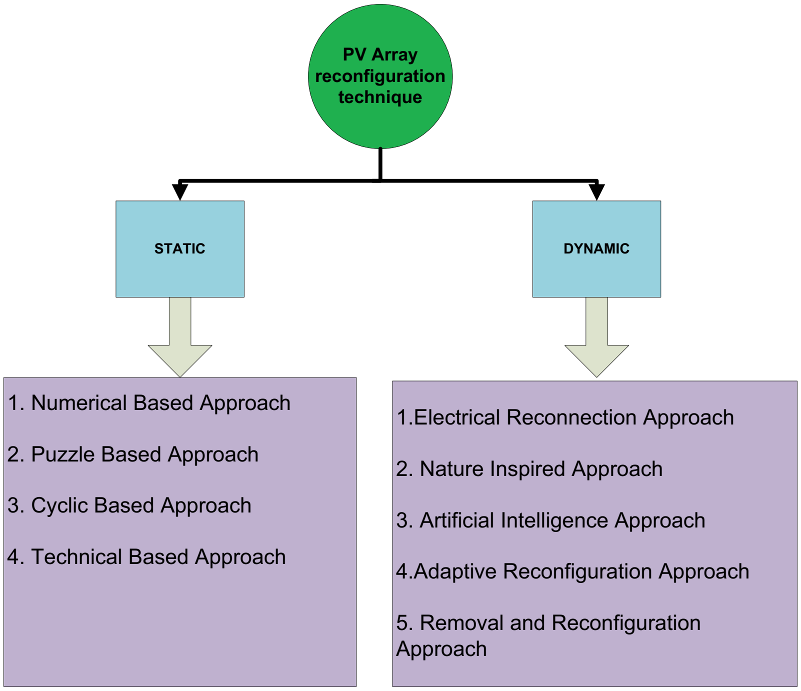


Figure 4. Classification of PV array reconfiguration technique.

3.1.1. Numerical based approach

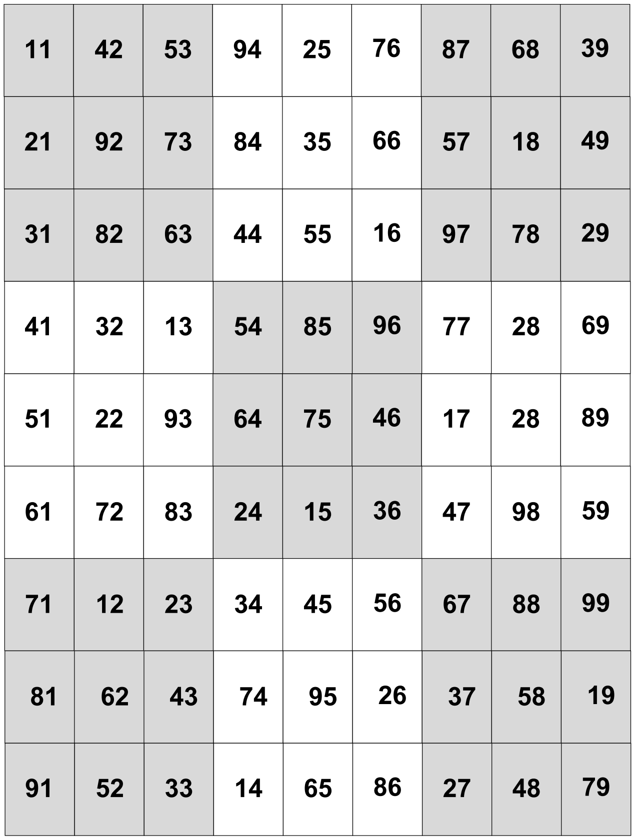
3.1.1.1. *Sudoku algorithm.* SuDoKu is a numerical based on logic [59]. Each row, column, and grid in the pattern for the SuDoKu-based puzzle must contain the digits 1 through 9 without duplicating any of them. The pattern is comprised of nine different 3 × 3grids. Each box's initial digit denotes the number, while the second digit represents the column that the number belongs to. It should come as no surprise that every submatrix, row, and column of the PV array has the capacity to store all of the numbers from 1 to 9. When it is determined that the SuDoKu puzzle pattern would result in an increase in the amount of PV electricity generated, the modules that make up the TCT connection are reconfigured so that they form the chosen puzzle design. In this case, the electric connection to the module does not change. On the other hand, the physical positioning of the modules is changed. While the connection to panel 42 (4th row, 2nd column) has been kept in place in the 4th row, the panel itself has been physically moved to the 1^{st} row, 2^{nd} column. The similar thing happens with panel number 22, which moves from the second row of the second column to the fifth row of the same column. But the PV panel is still attached to the 2nd row. So, the physical placement of the PV panels can be altered without altering how the panels are wired together. Since the array's electrical setup doesn't change, the equations for voltage (V) and current (I) stay identical as in the TCT connection [60].

In the Su Do Ku arrangement, the panels that were in the same row in the TCT connection are relocated to distinct rows. This makes it possible to suppress the amount of shade on the panels in the same row and spread the shade across the whole array. As a result, the SuDoKu configuration reduces panel bypassing and increases current approaching a node under partial shade scenario. So, even though the shading pattern stays the same, the array makes more power. In order to use the reconfiguration technique in real life, we need a no. of voltage and current sensors along with the switches; we need to alter how the modules are connected electrically. The 'Su Do Ku'-based solution that has been presented doesn't need any sensors or switches because the modules are permanently configured. Also, you don't need a separate control algorithm like you do with the reconfiguration technique [61–63]. Figure 5 represents SuDoKu reconfiguration pattern. Here the irradiance level taken is 900 W/m^2, 600 W/m^2, 400 W/m^2 and 200 W/m^2. The maximum power generated is 56.7 V_mI_m.

3.1.1.2. *Zig zag algorithm.* Another kind of static method is a Novel TCT (NTCT) configuration or a novel Zig-Zag reconfiguration mechanism. This technique entails moving panels physically to accommodate the modified framework. The Zig-Zag approach was suggested for a 4 × 3 connected TCT system by the authors of [64]. As part of this method, the PV modules in the first column of the PV string are kept in place while the modules in the very 1^{st} row of the TCT configuration are shifted to create the diagonal element. The Zig-Zag technique is used to reconfigure the 4 × 3TCT connected system's pattern in Figure 6. Here the irradiance level taken is 1000 W/m^2 and 500 W/m^2. The maximum power generated is 10 V_nI_n. By effectively implementing this approach, the authors showed that the Zig-Zag technique is better than the TCT configuration with regards of enhancing power output and reducing shading losses. This algorithm is applicable to large-scale systems. The advantage of this algorithm is that it can be applied to any dimension and its flexibility is low [65].

3.1.1.3. *Tom Tom pattern.* The primary rule of the TomTom (TT) pattern is that each row or column of the NxN array should be completely filled with digits from 1 to N, without repetition. Optimizing a photovoltaic system for maximum electricity output using the TT pattern, specific numbers must be placed in a certain manner within each sub-grid, as depicted in Figure 7, while using the predetermined calculation rule to get the desired value in the top left corner of each sub-grid. It has been discovered that the TT pattern greatly increases the PV system's power output [66–68]. Here the irradiance level taken is 900 W/m^2, 600 W/m^2, 400 W/m^2 and 200 W/m^2. The maximum power generated is 18 V_mI_m.

3.1.1.4. *Odd even technique.* A PV array's odd-even reconfiguration is a fixed technique. Previous research suggested the odd-even reconfiguration method for a 4 × 4TCT layout [69]. The PV modules were labeled as PV_{mn}, here m and n represent the row and column numbers, respectively. The PV modules were then rearranged in the odd-numbered row (PV_{11},PV_{13},PV_{31}, PV_{33}) and column (PV_{42}, PV_{22}, PV_{44}, PV_{24}) according to the configuration in Figure 8 [70]. This reconfiguration technique showed better performance and less mismatch loss than the traditional TCT configuration in shaded conditions. The odd-even reconfiguration approach helps to boost power generation by spreading out the shadow that sometimes forms over PV panels. The simplicity and ease of implementation are the notable advantages of this method. However, the primary



11	42	53	94	25	76	87	68	39
21	92	73	84	35	66	57	18	49
31	82	63	44	55	16	97	78	29
41	32	13	54	85	96	77	28	69
51	22	93	64	75	46	17	28	89
61	72	83	24	15	36	47	98	59
71	12	23	34	45	56	67	88	99
81	62	43	74	95	26	37	58	19
91	52	33	14	65	86	27	48	79

Figure 5. SUDOKU configuration.

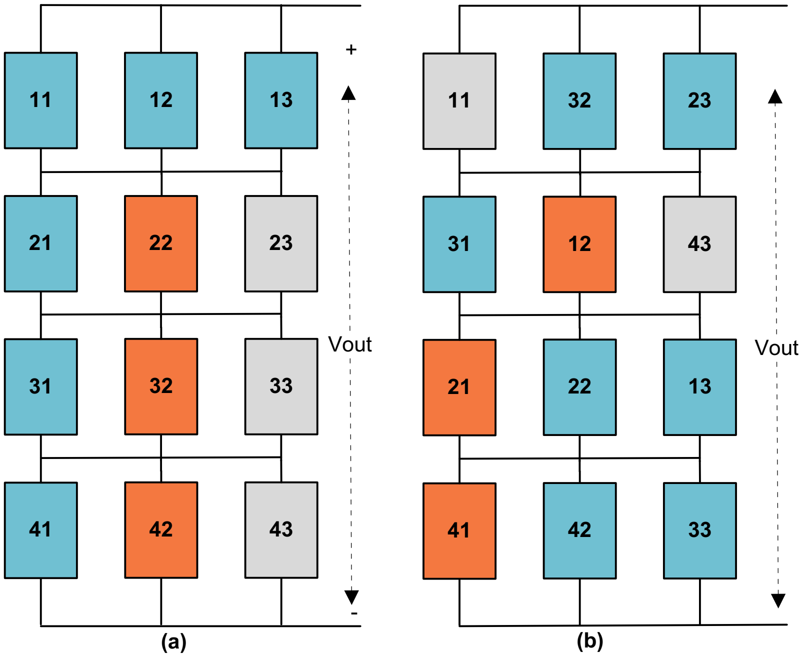


Figure 6. Zig-Zag scheme: (a) TCT configuration, (b) reconfigured pattern (zig-zag algorithm).

limitation of this technique is its applicability only to PV arrays with low power ratings, owing to the need for physically shifting PV modules [71,72]. Here the irradiance level taken is 1000 W/m^2, 600 W/m^2 and 300 W/m^2. The maximum power generated is 13.2 $V_m I_m$.

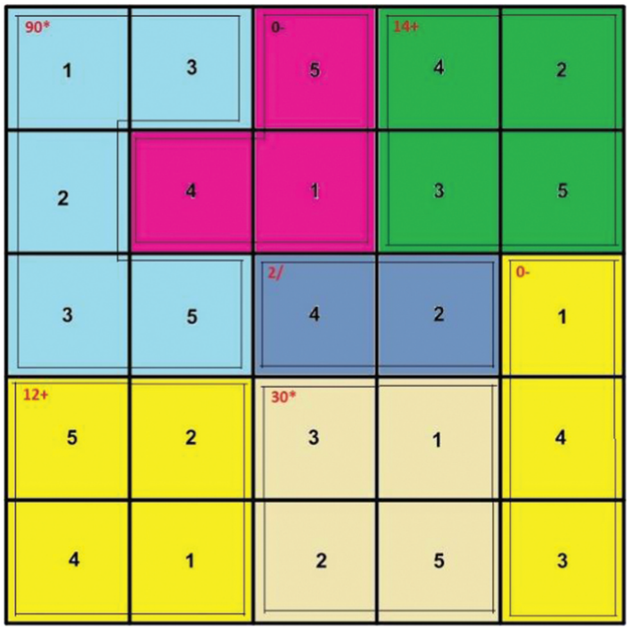
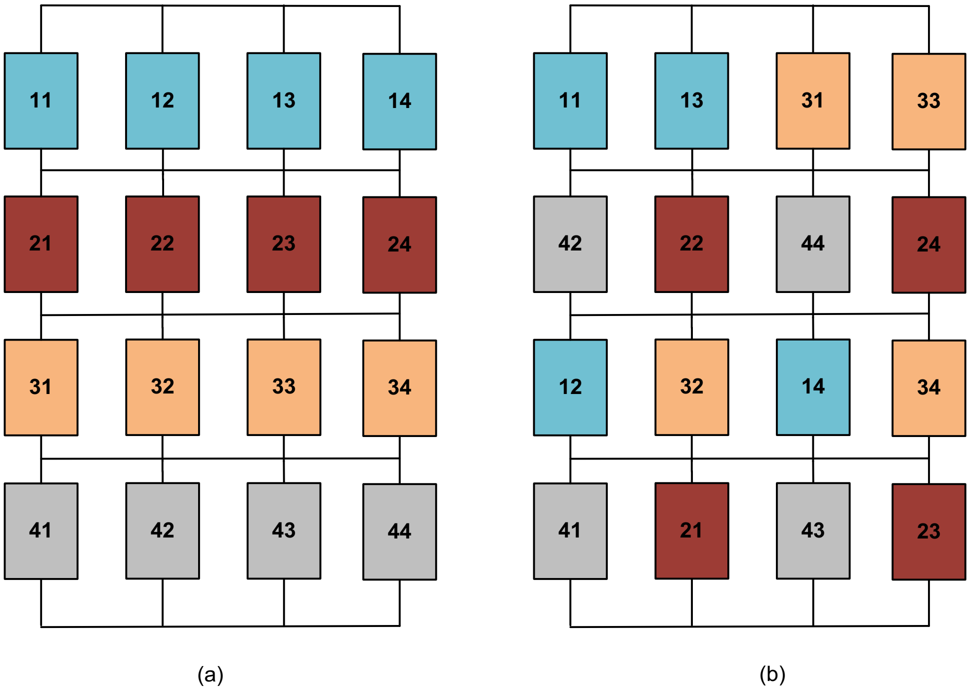


Figure 7. Tom Tom pattern.



(a) (b)

Figure 8. Odd-even reconfiguration technique, (a) TCT pattern, (b) reconfigured odd even technique.

3.1.1.5. Fixed electrical algorithm. The proposed approach, known as Physical Relocation of Modules with a Fixed Electrical Connection (PRM-FEC), is a novel strategy that centers on a specific mathematical principle [73]. The first column stays the same and the left columns move five places forward. Aside from the fact that EAR increases power by about the same amount, PRM-FEC is better because it costs less and is easier to set up because it needs fewer switches and sensors.

3.1.1.6. Column index algorithm. An easy and simple numerical programme and one-time physical relocation approach is the Column Index Algorithm (CIA) [74]. Also, CIA is better because it is easy to set up and has less wire loss.

The column index matrix is a two-dimensional matrix that represents the electrical links among the PV modules. The matrix has 'n' rows and 'm' columns, where 'n' is the number of PV modules in the array, and 'm' is the number of electrical configurations that can be used to connect the modules. Each element in the matrix represents the connection status of a PV module to a particular electrical configuration. The value '1' in an element implies that the corresponding PV module is connected in that configuration, while the value '0' indicates that the module is not connected. Initially, the column index matrix is initialized with all ones, representing a series-parallel connection of the PV modules. When partial shading is detected, the matrix is updated to reflect the new electrical connections between the PV modules to minimize the effect of shading. The matrix is updated by incrementing the adjacent columns to the shaded columns by one, while decrementing the shaded columns by one. This changes the electrical connections of the shaded modules to parallel or bypass diode connections, this can mitigate the effect of shade on the PV system's output. After the matrix is updated, the system checks for the maximum power point of the reconfigured PV array using an MPPT algorithm. If the maximum power point is increased, the reconfigured PV array output power is updated. If the maximum power point is not increased, the column index matrix is reset to the initial state.

3.1.1.7. Shadow dispersion scheme. An easy reconfiguration method based on certain numerical principles is the shadow dispersion scheme (SDS) [75]. Every column, except the first, decreases the grid by a distinct number of levels. Therefore, SDS reconfiguration is used to disperse intense shadows over distinct locations. Experimental findings confirm that SDS reduces PV array power loss under partial shading condition [76].

The proposed technique begins with a renumbering of the PV modules, which allows for the eventual acquisition of the SDS. After the modules have been renumbered, they are connected. The goal of the algorithm is to lessen the mismatch losses brought on by partial shading by distributing the effect of that shading across the entire array in the same way. The renumbering is carried out in a way that ensures a balance between the currents entering at each of the nodes. The objective of modifying the electrical configuration of the PV array is to optimize power generation by directing the current generated by the unshaded PV modules of a string to other unshaded strings, without compromising the performance of the shaded modules. Solar power modules in SDS are arranged differently than they would be in other interconnection schemes. The SDS arrangement disperses the shadowing effect across the entire PV array, mitigating its negative influence on a single row. This approach can enhance power generation during shading by increasing the incoming current in a specific node and minimizing the bypassing of PV modules.

3.1.1.8. API technique. The API technique is a new and innovative method to maximize energy harvesting from a PV array under variable shading conditions. It was introduced in a previous study by ref [77]. A PV array's efficiency is commonly diminished by shading, as it reduces the quantity of sunshine that reaches the solar cells. This results in a decrease in power production, which can be critical in applications where reliability and efficiency are essential. To overcome this limitation, the API technique proposes the use of alternate panel interchange, where the panels are rearranged in a specific sequence to maximize the amount of sunlight received by the array. The authors conducted simulations to compare the performance of the conventional and API techniques under different shading scenarios, including uniform shading, partial shading, and multiple shading. The results showed that the API technique outperformed the conventional technique in terms of power production, especially under partial and multiple shading conditions. The API technique can be easily implemented in existing PV arrays, as it does not require any additional hardware or complex control systems. It can also be customized to suit different shading conditions, making it a versatile and effective solution for improving the performance of PV arrays.

3.1.2. Puzzle based approach

3.1.2.1. Competence square (CS). This puzzle uses a logic-based number placement to find the alphabet/numbers that will solve a given (mn) matrix. Here, placement denotes the order in which the matrix's letters and digits are laid down. In addition, the row and column numbers that correspond to each panel location are appended to the position names. This strategy also has the additional benefits of being simple and straightforward to put into practice [78]. The Competence Square algorithm works by dividing the solar panel array into smaller sections, each of which is called a competence square. The algorithm then evaluates the power output of each competence square, taking into account factors such as shading and electrical resistance. Based on this evaluation, the algorithm determines which panels should be moved or reconfigured to optimize the power output of the entire system. By using the

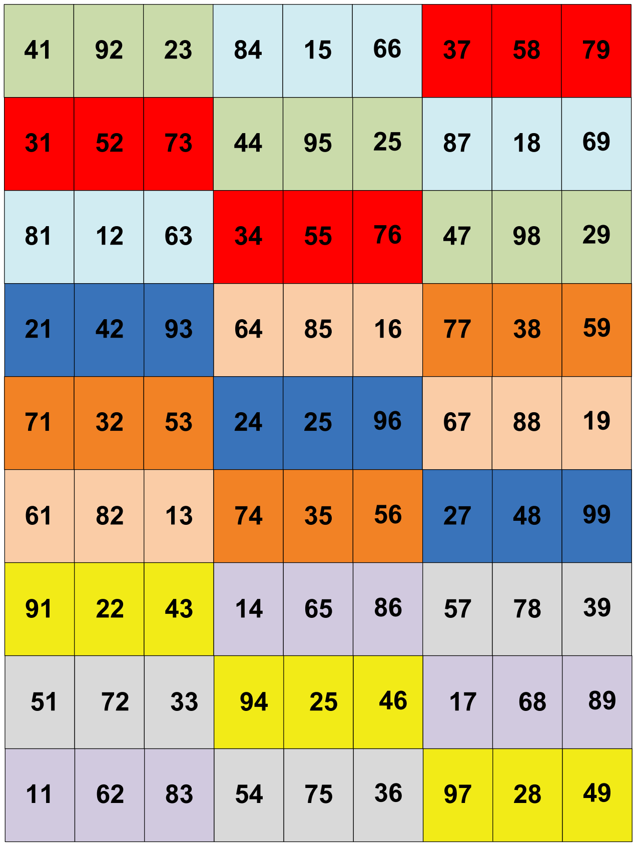
Competence Square algorithm, PV reconfiguration can be optimized to improve the power output of a solar panel system. This can lead to significant improvements in energy efficiency and cost savings, making it a valuable tool for solar energy professionals and businesses.

3.1.2.2. LoShu configuration. In reference [79,80], TCT, SuDoKu, DS (Dominant Square), CS (Competence Square), and Lo Shu based puzzle (9 × 9) PV array configurations are analyzed in detail using a critical approach. The analysis is conducted under various shading conditions, including SW, LW, LN, and SN shading circumstances (ranging from 200 W/m^2 to 900 W/m^2), and unique performance indicators such as capacity factor (CF), execution ratio (ER), and capture loss (CL) are presented in addition to standard metrics. The Lo Shu configuration is found to be the most effective among the PV array configurations considered in the study in terms of reducing Mismatch losses (ML) (2542W), minimizing PL (3%), achieving high CF (0.69), reducing CL (135.08), achieving maximum 91% ER, and reaching 100% level of PR parameters. Figure 9 depicts the schematic for the Lo Shu setup. Here the irradiance level taken is 500 W/m^2, 400 W/m^2 and 200 W/m^2. The maximum power generated is 56.7 $V_m I_m$.

3.1.2.3. Futoshiki configuration. Another static reconfiguration method that relies on puzzles is the Futoshiki approach. This method relies on the concept that moving PV panels physically while keeping the same electrical connections. The Futoshiki technique can be used to rearrange a PV array by ensuring that each row and column of the array contains the numbers 1 to m without any repetition. This approach can help to distribute shading across the PV array, reducing power losses. The Futoshiki scheme was employed for 5 × 5 photovoltaic array in article [81]. The numbers 1 to 5 were used to update the PV module positions in a 5 × 5 PV array, as seen in Figure 10. Here the irradiance level taken is 1000 W/m^2. The maximum power enhancement is 67.2%. The PV modules with lower irradiation will spread out when partial shading occurs, and according to the Futoshiki method, this helps to maintain the PV array's output voltage and the minimum row current. The collected findings demonstrated that this strategy outperforms the typical TCT design under shade conditions and reduces mismatch loss [82,83]. The application range is for small scale PV systems. The Futoshiki approach has unique solution. It is inapplicable for unsymmetrical array.

3.1.2.4. Magic square technique. The Magic Square (MS) matrix method is used to rearrange PV modules based on the mathematical concept that the sum of the numbers in any row, column, or diagonal is the same [84]. This approach is similar to solving a SuDoKu puzzle, where the physical positions of PV modules are rearranged. For an m×m PV array, the MS technique involves rearranging the no. of PV modules from 1 through m in such a way that every row, column, and main diagonal receives the same amount of sunlight. Figure 11 shows the 3 × 3 TCT linked array under consideration, and the reconfigured structure created by the Magic Square approach is depicted in the figure. Here the irradiance level taken is 900 W/m^2, 600 W/m^2 and 200 W/m^2. The maximum power generated is 5.1 $V_m I_m$.

In [85], the MS reconfiguration technique was used to reduce partial shading losses in basic configuration schemes. According to the primary findings, utilizing the MS configuration is a more effective method to modify the arrangement of a PV system, which reduces the impact of shading losses and leads to a rise in power generation. The MS reconfiguration technique was also presented in References [86,87]. The authors' findings show that the MS approach successfully disperses shade



41	92	23	84	15	66	37	58	79
31	52	73	44	95	25	87	18	69
81	12	63	34	55	76	47	98	29
21	42	93	64	85	16	77	38	59
71	32	53	24	25	96	67	88	19
61	82	13	74	35	56	27	48	99
91	22	43	14	65	86	57	78	39
51	72	33	94	25	46	17	68	89
11	62	83	54	75	36	97	28	49

Figure 9. Lo Shu setup.

11	12	13	14	15
21	22	23	24	25
31	32	33	34	35
41	42	43	44	45
51	52	53	54	55

(a)

11	42	33	54	25
21	52	43	34	15
31	22	53	14	45
51	12	23	44	35
41	32	13	24	55

(b)

Figure 10. 5×5 Futoshiki configuration, (a) TCT config., (b) reconfiguration using Futoshiki.

and aids in increasing power production under shady situations. This approach cannot be employed with PV plants that have a high rating.

A novel MS enhanced configuration (MS-EC) was put forth by the authors in ref [88]. as a static reconfiguration method for m×m TCT coupled systems. The proposed method for PV array configuration involves an improved approach based on the concept of creating a magic square. The algorithm is designed to ensure that the PV array is divided into two groups, with each group receiving the same or different levels of irradiation. This method is distinguished by the fact that it evenly spreads the shading over the array's PV panels, minimizing voltage drops and string currents caused by partial shading. The MS-EC method suggests clustering PV panels for the array, as they will all be in close proximity to one another and receive the same amount of sunlight [89–93].

3.1.2.5. Dominance square algorithm. A method called dominance square (DS) has been developed to restrict row current difference in a specific area, which can aid in producing an I-V curve with a single peak and

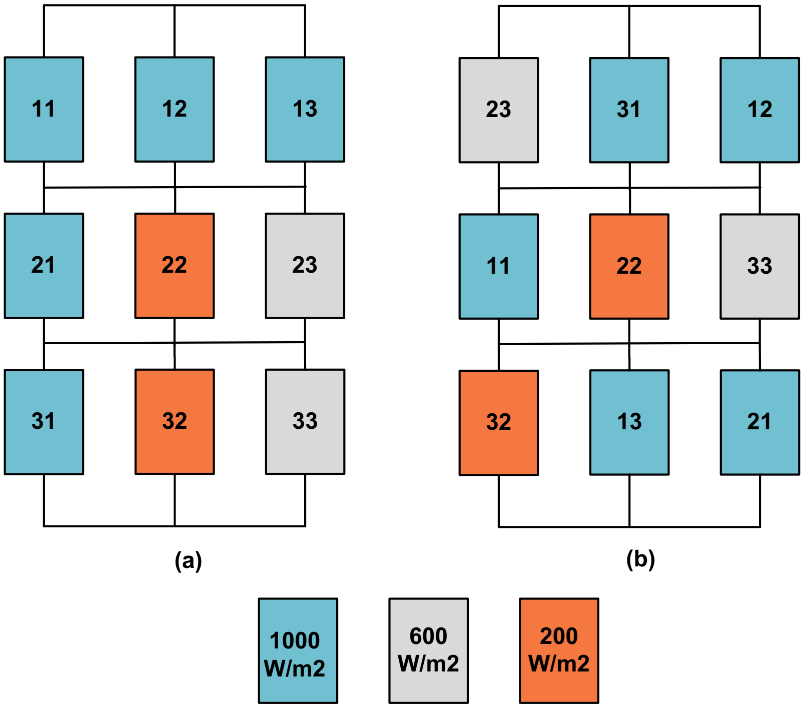


Figure 11. Magic square configuration, (a) 3×3 TCT configuration, (b) reconfiguration using magic square technique.

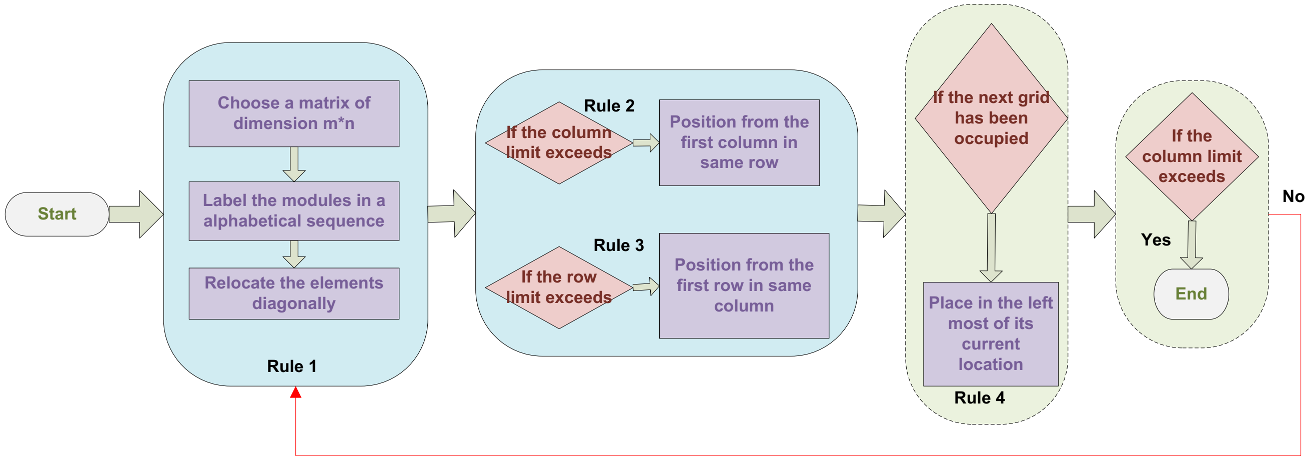


Figure 12. Flowchart of dominance square algorithm.

low degree of dispersion [94]. Nevertheless, it might not work well for massive PV installations. Figure 12 depicts the reconfiguration procedure for DS. The numbers in a square matrix are placed in a grid that resembles a dominant square puzzle. This puzzle makes use of logical number placements to place a number or alphabet in a specific spot in order to solve a particular matrix. Positioning in this context means putting the digits or letters in a specific order.

3.1.2.6. Square arrangement algorithm. The consequence of shade dispersion on 3 × 3 and 5 × 5 TCT PV arrays is detected via the square arrangement algorithm (SAA). The power loss brought on by PSC and the voltage drop brought on by the activation of bypass diodes are both lessened by SAA. Simulations demonstrate that SAA can generate more power than conventional connections with a single physical reconfiguration [88].

The algorithm starts with the premise that two groups of modules exist within a PV array, one of which is always exposed to the same amount of light as its neighbours, while the other is exposed to light that is significantly weaker. The purpose of this technique is to rearrange all of these PV modules in order that their shading effects are evenly spread across the area they cover without relocating any of them. By turning on the bypass diode, you can limit the current through the string and prevent the terminal voltage from falling when the modules are shaded. Once the PV modules' positions have been assigned and the normal solar irradiations have been established, only then should this strategy be implemented prior to the PV array being commissioned. With the modules' placements remaining the same, this approach is used to determine the physical electrical connections, which won't change.

3.1.3. *Cyclic based approach*

3.1.3.1. Ladder configuration. In a Ladder configuration, alternating rows are connected by cross ties. The authors have developed a ladder configuration in addition to the traditional PV configuration for performance assessment at blocked irradiance levels ranging from 300W/m^2 to 1000W/m^2. The results of efficient performance index output, including V_{oc}, I_{sc},V_m, I_m, P_m, PL (power losses), ML (mismatch losses), and FF (fill factor), show that hybrid and ladder based designs perform better than other options in all climatic circumstances [95]. Figure 13 displays the ladder configuration. Here the irradiance level taken is 900 W/m^2, 600 W/m^2, 400 W/m^2 and 200 W/m^2. The maximum power enhancement is 19.9%.

The BL configuration can experience shading issues if one panel is partially shaded, which can significantly reduce the overall power output. Similarly, the SP configuration can suffer from a similar issue if one section of the panel is shaded. So, the limitations of the BL and SP PV array configurations are overcome by this Ladder PV setup. When using this Ladder layout, the PV modules in the first two columns of a given row were connected in parallel, and the remaining PV modules in that row were connected in series. The Ladder setup's architecture resembles a ladder. In a Ladder PV array, the voltage across each module in a row is equal to the Voc of every single PV panel. Adding up the current produced by each PV panel in the array yields the output current of the array. Ladder's panel structure is not serial, but its rows are.

A unique work described in [96–98] involves using fewer switches to connect the electrical components of the PV array system. Additional investigation on a 2 step reconfiguration technique is conducted under various, realistic shadowing patterns (200 W/m^2-950 W/

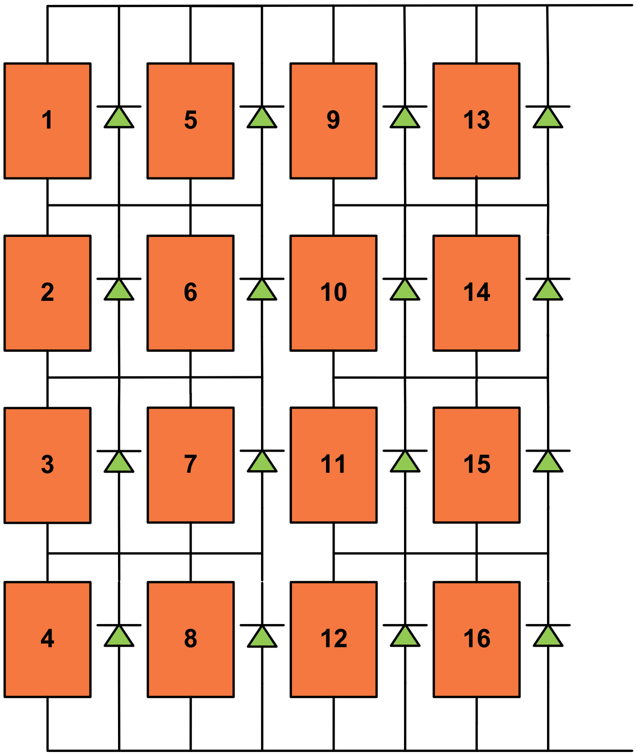


Figure 13. Ladder configuration.

m^2). Using the SuDoKu puzzle, the proposed configuration is rearranged and split into little submatrices of 2 × 4size, and during experimentation, minimal ML values of 6.7%, 8%, 9.9%, 23.7%, and 5% are obtained relative to others.

3.1.3.2. Two phase array reconfiguration algorithm.

Static reconfiguration techniques have certain limitations when it comes to accurately defining or determining shadow dispersion in a PV array system architecture. To address this issue and optimize PV energy production, a new two-phase array reconfiguration (TPAR) method has been introduced in the literature. TPAR involves dividing the entire PV array into multiple smaller sub-arrays, relocating the panels within each sub-array, reconfiguring each sub-array, and finally moving them by switching the columns of the sub-arrays. This four-step process intends to maximize the output of the PV array and overcome the limitations of previous methods. Simulation testing have shown that TPAR significantly reduces power loss for all forms of shadows [26].

3.1.4. Technical based approach

3.1.4.1. Skyscraper puzzle technique. BIPV (Building-integrated photovoltaic) systems are installed on the roofs of buildings or other vacant spaces. To come up with a fresh concept for PV array reconfiguration, a unique skyscraper scheme (SS) technique that imitates the architectural program of building groups with varying heights has been devised [99]. When more cable lines are required to move PV modules, there is a voltage drop that results in power loss, known as wiring loss. More wiring loss will take place as the cable line gets longer. Hence, by using eq. (1) [100] to calculate the wiring loss, the superiority of SS over AS can be shown by contrasting the length of cables used in each technique.

$$Wiring\ loss\% = \frac{L_{SS} - L_{AS}}{L_{AS}} * 100\% \qquad (1)$$

where L_{SS} and L_{AS} are, respectively, the SS and AS configuration's cable lengths.

One advantage of this method is its ability to function effectively in a variety of conditions. It can also be expanded to handle more complex scenarios and is well-suited for real-time use [101–103].

3.1.4.2. Chaotic baker map algorithm. The Chaotic Baker Map (CBM) is a technique in computer engineering that uses randomly modified pixel coordinates to secure communication in image processing [104]. Moving panels to different locations within an array using the CBM technique allows for optimal configuration of photovoltaic (PV) systems, where the actual placements of panels can be thought of as pixel positions [105]. The technique involves initially dividing an NxN PV array into 'k' rectangles and then scanning each rectangle to create a new row for the array. In the end, these rows will be combined to produce a whole new array. The advantage of CBM is that it automatically selects the best algorithm key from a large pool of candidate keys. Additionally, because CBM lacks electrical components like switches and sensors, it has the ability to create BIPV arrays and substantial solar farms [106–108].

3.2. Dynamic reconfiguration

Dynamic reconfiguration is an appropriate technique to increase a PV's ability to generate power during PSC. This method can be applied in a number of discrete ways, such as (i) implementing switches across the interconnections of PV modules, (ii) clustering PV panels according to the shaded sections to minimize shading losses, and (iii) adjusting the series and parallel array to balance the row current with a switching matrix. The control technique uses the switching conditions provided by the switching matrix to dynamically reorganize the PV array during PSC [109].

Premature ageing and damage to the PV have also been taken into consideration, along with a dynamic reconfiguration with an appropriate objective function to obtain the necessary compromise between power conversion efficiency and amplitude of thermal stresses [110]. Particle swarm optimization (PSO), gross hopper (GH), munkres algorithm (MAA), and other strategies that use mathematical computations, fuzzy logic, neural networking, and evolutionary genetic algorithm (GA) have been presented for reconfiguration and optimization of a dynamic Electrical Array Reconfiguration (EAR) method [111], where relocation has been taken into account based on the amount of shaded array and where they are located within the array.

3.2.1. Electrical reconnection approach

3.2.1.1. Irradiation equivalence by relocation of panels. The goal of the method is to move PV panels from one row to another in order to ensure that no series of PV panels limits the current flowing through the system [17]. While this technique is similar to electrical array reconfiguration, it varies in that the shadowed panels are not disconnected but instead linked to other rows in order to reduce current imbalance. The no. of panels linked in series and parallel remains intact both before and after the switch. The energy yield is improved by adjusting the PV array's panel placement to account for the current shading conditions. This balances irradiation, prevents bypass diodes from activating, and improves irradiation. Finding the ideal panel location is difficult, even for a smaller array, due to the vast number of possible configurations [112]. For instance, there are 16! (15×10^{24}) different ways that a 5×5 array could be configured. This includes a lot of redundant setups, and the unique number of configurations, also known as the configurations of interest (N_{ci}), is provided by:

$$N_{ci} = \frac{(m * n)!}{m! * n!^{m}} \tag{2}$$

Now, there are just 5×10^{12} configurations, which is still a sizable quantity. It is not possible to move panels around dynamically; instead, the effect is simulated by switching how the panels are connected to one another. 2*m*n single pole 'm' throw switches are needed for a m×n array.

The primary constraints on these approaches are the complexity of the calculation and the need for sensors and switches [113–115].

3.2.1.2. Dynamic electrical scheme. The Dynamic Electrical Scheme (DES) aims to distribute multiple PV modules across various rows with equivalent levels of irradiance. To achieve this goal, the method proposes two different control algorithms, deterministic and random search algorithms, for calculating irradiance equalization. The random search process, however, is dependent upon the finishing condition. The optimized PV array's minimum ($N_{Row_{min}}$) and maximum ($N_{Row_{max}}$) row numbers are first established [116]. The algorithm begins by seeking the optimal arrangement, starting with a set of rows (N_{Rows}) equivalent to ($N_{Row_{min}}$). To achieve this, the first (N_{Rows}) modules of the descending sequence are placed in individual rows, while the following modules are attached one at a time to the row with the lowest irradiance sum of the already placed modules. All modules have been located after the most recent iteration, and the total number of rows that have been irradiated is known [117]. The Equalization Index (EI) is then computed by the procedure (see Eq. (3)) and stored. This increases the number of rows (N_{Rows}), and the process is continued until (N_{Rows}) equals ($N_{Row_{min}}$). The arrangement that reduces the EI is ultimately the best one. For DES implementation, the necessary number of switches is given by eq. (4),

$$EI = Max(G_i) - Min(G_i)\forall i \tag{3}$$

$$N_{SW} = \left(2mN_{pv}\right)_{DPST} + (m)_{SPST} \tag{4}$$

whereas SPST and DPST indicate single-pole and double-pole switches, respectively. The no. of PV modules is N_{pv}, while the no. of rows is m [37,118,119].

3.2.1.3. Electrical array reconfiguration (EAR). According to the row current and irradiation levels, the PV array is reconfigured using the EAR approach. The EAR system utilizes data obtained from a data acquisition system to analyze irradiance, which then helps in producing the most favorable switching situations for PV modules. Digital signal processors, microcontrollers, and field programmable gate arrays are some of the devices that are commonly used to configure the switching matrix [120]. Figure 14 displays an EAR system equipped with a switching mechanism that can modify a PV array's series and parallel configuration. Here the irradiance level taken is 100 W/m^2, 200 W/m^2, 300 W/m^2, 400 W/m^2 and 500 W/m^2.

The PV array reconfiguration technique involves altering the connections between PV panels by turning them on and off in response to varying levels of shade. The method relies on the PV modules' maximum and lowest voltages to accomplish the switch. By using mechanical switches, the interconnections between the PV array can be altered dynamically. The creators of a particular method measured irradiation levels and

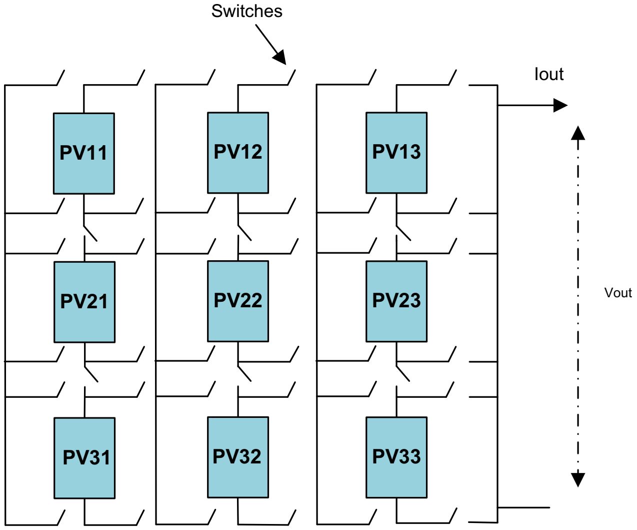


Figure 14. EAR setup.

took into account the short circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of a PV array in order to identify beneficial connections. Mechanical switches are utilized to expand the array size in this method. However, driver circuits are also needed to operate the system, which adds to the system's size and cost. In a related study [121], the author devised an array reconfiguration method for a 9 × 9 PV module array that utilizes PV modules with lower ratings. The previously mentioned EAR techniques have drawbacks since their controllers are time-consuming, complex, and involve several switches, driver circuit design, and sensors [122–124].

3.2.1.4. Munkres algorithm. A subset sum problem-based control system is designed to accomplish optimal reconfiguration of PV arrays. In the control system's post-processing phase, the Munkres algorithm modifies the switch architecture to lessen switch activity and increase switch longevity [37]. Figure 15 also shows the reconfiguration impact of the Munkres algorithm, which equalizes the illumination of each row, Figure 15(a) presents the initial configuration while Figure 15(b) presents the arrangement after reconfiguration. Here the irradiance level taken is 100 W/m^2, 300 W/m^2 and 900 W/m^2.

One way to use the Munkres algorithm for PV reconfiguration is to represent the PV system as a bipartite graph, where the PV modules are represented by one set of nodes, and the inverters or other electrical components are represented by the other set of nodes. The PV modules' and inverters' connections are represented by the weights of the edges between the nodes, which in turn represent the costs and benefits of such links. The Munkres algorithm can then be used to find the minimum-weight perfect matching of the graph, which corresponds to the optimal configuration of the PV system.

Another way to use the Munkres algorithm for PV reconfiguration is to use it to optimize the placement of PV modules on a given surface, such as a rooftop or a ground-mounted system. The Munkres algorithm can be used to find the optimal placement of PV modules that maximizes the power output or efficiency of the system, while taking into account factors such as shading, orientation, and distance between modules.

3.2.2. Nature inspired approach

3.2.2.1. Marine predators algorithms. The Marine Predators algorithm (MPA) imitates how predators

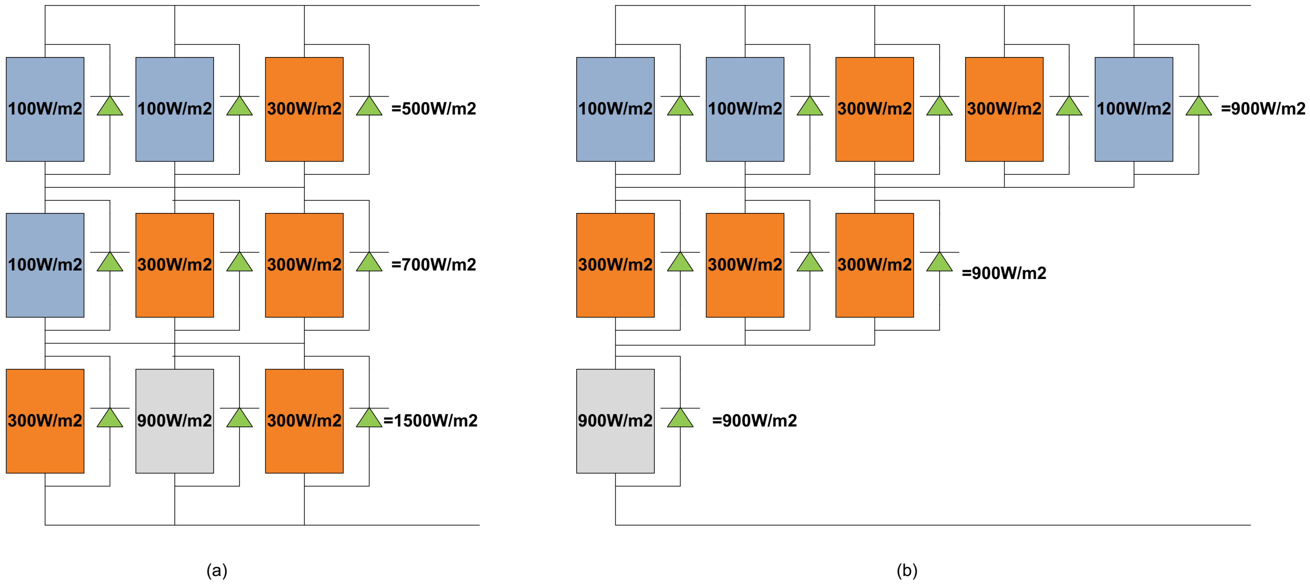


Figure 15. Munkres algorithm, (a) initial circuit, (b) post reconfiguration.

and prey behave in the ocean. To prevent early convergence caused by erroneous weights values, MPA creatively introduces a new objective function, which is given by eq. (5) [125] as follows:

$$Function(i) = \frac{P_{array}}{|I_{max} - I_{min}|} \tag{5}$$

The function takes in the maximum and minimum row currents as I_{max} and I_{min} respectively, while the fitness of population member i, denoted by the function (i), is shown here. The major goal of the function is to optimize power output at the expense of the current differential between rows. MPA is noted to outperform other optimization algorithms like Particle Swarm Optimization (PSO), Harris Hawks Optimization (HHO), and Manta Ray Foraging Optimization (MRFO) as it is able to evaluate the optimal configuration in a shorter time on average [126–129].

3.2.2.2. Butterfly optimization algorithm. A bio-inspired program known as the Butterfly Optimization Algorithm (BOA) was created recently and mimics the foraging and mating behaviors of butterflies [120,130]. For some shadow patterns, BOA generally harvests more PV system output power under PSC than GWO. The process kicks off with the input of the solar array's dimensions and the photovoltaic module's electrical attributes. The best matrix is then obtained after updating solutions using BOA [131,132].

3.2.2.3. Water cycle algorithm. The Water Cycle Algorithm (WCA) was created because of the idea of the water cycle, in which water travels through streams and rivers to the ocean. Reconfiguring PV arrays with WCA reduces power losses and IMI [133]. The natural water cycle served as inspiration for the water cycle algorithm, which is an optimization meta-heuristic that mimics the natural flow of water from rivers and streams to the ocean. When water evaporates from rivers, lakes, and streams and when plants exude water through photosynthesis, the hydrologic cycle begins. The water vapour rises into the cooler part of the atmosphere, where it condenses into clouds and falls back to Earth as precipitation. WCA's seed population is referred to as 'raindrops'. In this analogy, the best raindrop is the sea, a certain number of good raindrops are the river, and the remaining raindrops are the streams. Numerous disciplines, including water resources management, civil engineering, mechanical engineering, and mathematics, have made use of water cycle algorithms. For a fixed number of solutions, the Water Cycle Algorithm uses Raindrops as its variables. One limitation of the WCA is its relatively slow execution time, which makes it inappropriate for use in real-time application of large-scale solar arrays [134–136].

3.2.2.4. Gravitational search algorithm (GSA). The GSA is a nature-inspired algorithm that relies on Newton's laws of motion and the idea of universal gravitation. Its main objective is to reduce the index of irradiance level mismatch (IMI), that is determined by summing of squares of the differences between the illumination intensities of the PV rows [137–139]. GSA has been used for the reconfiguration of PV arrays, and when compared to BBA, it has shown to have a significantly faster optimization time.

3.2.2.5. Grey wolf optimization algorithm. In Grey wolf optimization (GWO) the population is made up of 4 different types of wolves, namely alpha (α), beta (β), delta (δ), and omega (ω), simulates the collaborative hunting methods of grey wolves in large part. A consistent observation is that the lowest-ranked grey wolves, referred to as omega (ω), tend to act as the followers and scapegoats [140].

Additionally, the multi-objective grey wolf optimizer (MOGWO), a modified form of GWO, is suggested to increase power production by decreasing the difference between neighboring row currents that is advantageous for smoothing PV curves. These two conflicting goals, in particular, can be stated mathematically as

$$Max(Obj_1) = sum(P_x) = \sum\nolimits_{x=1}^{9} I_x * V_x \tag{6}$$

$$Min(Obj_2) = |I_{max} - I_{min}| \tag{7}$$

The maximum and minimum values of the current in a row are represented by I_{max} and I_{min}, respectively, while the voltage and current of the PV array for the xth row are represented by V_x and I_x. According to simulation tests, MOGWO effectively resolves the multipeak problem and improves power generation by 9.4% to 18.8% compared to TCT [141–143].

3.2.2.6. Particle swarm optimization (PSO). In order to determine the optimal reconfiguration of PV module/array when shadowing or malfunctioning conditions are present, an optimization process called particle swarm is utilised. The particle swarm optimization (PSO) approach is well-known for its versatility and simplicity because it depends on a parallel, spontaneous search strategy. Altering the wiring connections rather than moving the modules is what this method entails. Particle Swarm Optimization, having shown its dominance in the area of optimization, is appropriately selected for its computing skill and rapid convergence. Particle Swarm Optimization is a highly durable approach with a proven ability to handle vast solution spaces [144,145]. The PSO approach has various benefits, including its easy-to-implement code and reliance on parallel processing to rapidly arrive at the optimal reconfiguration. In addition to this, the PSO approach assures that there is less of a chance of the system converging on a solution that is only valid locally.

3.2.2.7. Grasshopper optimization algorithm (GOA).

The GOA algorithm is used to reduce the consequences of Partial Shading Condition because of its low complexity and fewer controllable variables [146]. GOA improves the optimization effectiveness of the method but also raises its computational complexity because it changes the solution during the iteration phase by taking into account the current position of each unit and the global optimal solution. In conclusion, GOA is efficient in mitigating the effect of Partial Shading Conditions, although it does necessitate a more powerful computer's processing speed. Mathematical models of grasshopper swarm behaviour look like this:

$$X_i(t+1) = c\left[\sum_{\substack{j=1\\ j\neq i}}^{N} c\frac{ub_d - lb_d}{c}\, s\left(\left|X_j(t) - X_i(t)\right|\right)\frac{x_j(t) - x_i(t)}{d_{ij}}\right] + T_d \tag{8}$$

$$s(r) = fexp\left(\frac{-r}{l_s}\right) - \exp(-r) \tag{9}$$

where $X_i(t+1)$ is the current location of the i_{th} grasshopper, f the strength of attraction, r a distance, l_s the attractive length, ub_d and lb_d the upper and lower bounds, s is a function representing the strength of social forces, d_{ij} the distance between the i_{th} and j_{th} grasshoppers, T_d the target of a position in dimension d, and c the shrinking factor representing the comfort zone contracting.

3.2.2.8. Modified Harris Hawk optimizer algorithm.

A new approach to reconfiguration based on the modified Harris hawk's optimizer has been proposed in the literature to address the shortcomings of GOA [147]. This technique mimics the predatory techniques of Harris hawks. MHHO surpasses other methods in terms of reconfiguration while utilizing just 12.5% of the repeating values of GA and produces extra power, as shown by simulation experiments comparing MHHO to CS, HHO, PSO, GA, and MHHO.

Due to the optimization nature of PV reconfiguration, a dependable algorithm providing an ideal reconfiguration structure to reduce system mismatch losses is required. To do this, the researchers present a new Modified Harris Hawks optimizer (MHHO). The HHO performs well in the exploitation phase, but it needs to improve its exploration phase to prevent getting stuck on merely local solutions too quickly [39]. In addition, the imbalance between the discovery and exploitation stages is caused by HHO's reliance on a linear determining function in estimating the prey energy. After a moderate no. of iterations, the algorithm enters an exploitation phase during which agents may or may not have converged on the global solution. This problem leads to an untimely arrival to the local optimum. In light of this, the authors recommend a change to the described exploration tactics, focusing on the fundamental HHO and the distribution of the escaping energy throughout the number of repetitions.

3.2.3. Artificial intelligence approach

3.2.3.1. Artificial ecosystem based algorithm.

The energy flow of the biosphere is used to generate an AEO, or artificial ecosystem-based algorithm. The behaviours of production, consumption, and decomposition are replicated by AEO [148]. In the article [149], AEO is used to reduce PV system mismatch loss. A new objective function is used to fix the issue where the weight coefficient has a major impact on the final solution's quality.

$$Max(f) = \frac{Max(p)}{STD(I)} \tag{10}$$

$$p = [p1, p2, p3, \ldots p9], I = [I1, I2, I3, \ldots .I9] \tag{11}$$

where $STD(I)$ notation for the standard deviation of the row currents in vector 'I' [150,151].

3.2.3.2. Machine learning algorithm.

The use of cyber-physical systems in conjunction with machine learning algorithms (MLAs) enables the development of robust signal processing capabilities [152]. In particular, a machine learning model is used to construct a function that generates an irradiance profile for the purpose of photovoltaic (PV) array reconfiguration. In general, MLA achieves an approximate of 12% increase in power in comparison to other reconfiguration techniques.

3.2.3.3. Clonal selection algorithm. The clonal selection algorithm is designed to imitate the functions of the immune system in biology, where memory and learning components handle the processing of information [153]. The goal function used by the clonal selection method to determine the ideal configuration is constructed as follows:

$$F_i = \frac{\sum_{j=1}^{n} \left(G_{avg}\right)_j}{n}, \text{for i} = 1, 2, \ldots \text{m} \tag{12}$$

$$\min(|F_{i+1} - F_i|) \tag{13}$$

where the fitness value is denoted by F_i, while $\left(G_{avg}\right)_j$ represents the average irradiance value of the j^{th} row, with m (row) and n (column) numbers. The combined module decides whether or not to utilize a suboptimal solution rather than implementing the best option proposed by the clonal selection process [154].

3.2.4. Adaptive reconfiguration approach

3.2.4.1. Adaptive array reconfiguration. The panels are divided into two groups in the Adaptive Array Reconfiguration (AAR) scheme [155]: the fixed bank and the adaptive bank.

Since only the adaptive portion is configurable, the switching needs are significantly decreased by this partial reconfiguration technique. The PV modules in the stationary array are arranged in a TCT configuration that remains fixed. When irradiation is uniform, the switching matrix links each row of the stationary array equally to the reconfigurable modules in the adaptive array. However, the no. of adaptive array modules which are connected to each row of the stationary array is dynamically determined based on the current shading conditions during non-uniform irradiation or partial shading scenarios. rows that contain additional darkened modules or strongly shaded modules will receive a greater proportion of adaptive array modules to create balance with the other rows of the stationary TCT array. As a result, the output is improved, and the current mismatch between the rows of the fixed bank is decreased. An algorithm that is either intelligent or evolutionary controls the switching matrix. To properly address all sorts (patterns) of shading, these approaches need a large adaptive bank. The system's overall size and expense are increased by this method's additional use of more sensors and switches in addition to a complex control algorithm [156].

After careful consideration, the location for such an installation is chosen, and it is unlikely that any physical structures will partially shade it [32]. The PV array can be covered in dust and grime or by a passing cloud. While the latter can be avoided with adequate maintenance, the former lasts for a shorter period of time. The dynamic reconfiguration (EAR, Repositioning, and AAR) solutions require a greater number of switches, making them inappropriate for installations of a huge scale [132,157].

3.2.4.2. Bubble sort algorithm. The Bubble sort algorithm (BSA) is a sorting method that involves several iterations through a list of elements that need to be sorted. During each iteration, it compares two adjacent elements and swaps their positions if they are not in the correct order. The algorithm is employed for the purpose of arranging the rows of a predetermined section in a sequential manner, with the aim of aligning every adaptable photovoltaic (PV) unit with its respective row, according to voltage. The efficacy of BSA in augmenting power generation has been substantiated through the outcomes of an experiment conducted on a 3 × 3 Photovoltaic PV array [158].

3.2.4.3. Configuration scanning algorithm (CSA). The CSA is a method that evaluates all potential configurations and selects the best one for reconfiguring PV arrays. With no software or hardware modifications, CSA can be used in PV systems of varying power levels to ensure short circuit currents are distributed uniformly across all rows [22].

3.2.5. Removal and reconfiguration approach

3.2.5.1. Reconfiguration based on selection. Redistributing modules in such a way as to create an even distribution while simultaneously ensuring that each column keeps more than fifty percent of its original modules is what the process of selection-based reconfiguration implies. The efficacy of this strategy in increasing the output power and operational voltage of a photovoltaic (PV) array when it is subjected to PSC has been validated by empirical studies. Though, this technique may not be appropriate for minor shadows since it does not produce significant power enhancements in such scenarios [159].

3.2.5.2. Power comparison algorithm (PCA). The power comparison method is used to rearrange the remaining PV modules in an array so that the p-I and V-I curves are more flat and uniform. Highest power point (MPP) analysis is used to determine the optimal PV setup for highest power output. The most optimal PV array arrangement is the one that results in the highest MPP. Power loss can be decreased by using PCA, according to simulation testing [160].

4. Result and discussion

The authors of this research surveyed the available literature and selected strategies for reconfiguring PV arrays to mitigate partial shading. There are two main types of these methods: static and dynamic. 38 strategies have been taken for static while 40 strategies are taken for dynamic reconfiguration. Table 1 shows the comparison of various static PV reconfiguration strategies and Table 2 shows the comparison of various dynamic PV reconfiguration strategies.

The use of specific array pattern layouts, such as SuDoKu, optimum SuDoKu, Magic square, Futoshiki, and Dominant-Square, among others, is a common strategy in the static method to mitigate the impact of partial shading on photovoltaic systems. These layout schemes have received a lot of attention in publications. On the other hand, there are pros and cons to any setup. However, there are certain limitations to the static approach. To begin with, rearranging PV modules demands a significant amount of physical effort and wiring. Furthermore, irrespective of the PV array rearrangement, the first column of the array remains unchanged. Consequently, the power output reduces, and if shading occurs on the left side of the array, the p-V curve displays many peaks. Additionally, this method may not be able to evenly disperse the shading effects in rare situations such as mutual shadow or rapidly moving clouds. The primary disadvantage of this method is that it is not self-reconfiguring.

To combat the mismatch phenomena and boost power output from PV plants, the dynamic approach can be employed instead of the distributed MPPT. However, in order to implement this method, you'll need a monitoring system that can measure the PV module's physical and electrical properties, an approach to figure out how to best arrange the PV modules, and a switching matrix to connect them all together. Because of this, the dynamic approach will become more expensive, but it will be able to make up for the difference by producing the most possible power from the PV system. The process of determining the optimal electrical switching combination for the physical relocation method can be difficult and time-consuming. To address these concerns, optimization strategies may be a potential alternative. When it comes to determining the optimal switching configuration to disperse shade effects uniformly across the PV array, optimization approaches are well-known to shine due to their ability to deal with many objectives at once. The dynamic approach that makes use of a microprocessor or field-programmable gate array-based technology is highly recommended for real-time applications. Dynamic techniques have the added advantage of avoiding hot-spot effects by eliminating multiple peaks under shading conditions.

5. Conclusion

This study offers a thorough examination of static and dynamic reconfiguration techniques for photovoltaic arrays, classifying each method according to its distinct features. The analysis conducted evaluates these strategies based on several parameters, such as complexity, array size suitability, shadow patterns, as well as their respective pros and disadvantages. Our research suggests that static reconfiguration methods are typically less complicated, which makes them appropriate for smaller and less complicated photovoltaic installations. Nevertheless, the practical application of PV panels in real-life situations might pose challenges due to the logistical complexities involved in physically moving them. Although there are limitations, static approaches continue to be beneficial due to their simplicity and little maintenance needs. However, dynamic reconfiguration approaches, despite being more costly since they require multiple sensors, switches, and integrated devices, provide better performance. These techniques offer a quick reaction to shifting shade patterns and increased flexibility to different

Table 1. Comparison of various static PV reconfiguration strategies.

S. No.	Reconfiguration Strategies	Array Size	Type of shadow	Complexity	Merit/Demerit	Validation	Ref.
1.	SuDoKu Algorithm	9×9	SW, SN, LW, LN	Low	Simple to put into action; There's no need for a sensor; Low voltage and substantial current loss in the wiring.	Simulation	[59–63]
2.	Zig-Zag Algorithm	4×3	Double row, single row, corner shadowing, oblique shadowing	High	Can be applied to any dimension, less flexibility.	Simulation	[64,65]
3.	Tom-Tom pattern	5×5	LW, SN, SW, LN, left and right upper, left and right lower	Moderate	No sensors required; rules are complex.	Simulation	[66–68]
4.	Odd-Even technique	4×4	SW, SN, LW, LN	Low	Lessens LMPPs, shading dispersion is lower.	Experimental/ Simulation	[28,69–72]
5.	Fixed Electrical Algorithm	7×5	SW, SN	High	It enhances the row current; it has real time implementation; it has low flexibility	Experimental/ Simulation	[73]
6.	Column Index Algorithm	9×9	SW, SN, LW, LN	Moderate	It has less wire losses; It has less flexibility	Simulation	[74]
7.	Shadow Dispersion Scheme	3×3, 7×7	LN, SW, center, L pattern, one module shadowing	High	Drastically cut down on mismatch losses; Modules in the first column remain fixed.	Experimental/ Simulation	[75,76]
8.	API Technique	9×9	SW, SN, LW, LN	High	improved energy efficiency, reduced costs, and enhanced system performance. need for additional hardware or software tools, increased maintenance requirements, and the cost of implementing the reconfiguration	Simulation	[77]
9.	CS (Competence Square)	9×9	SW, LW, LN, SN	Moderate	Simple and easy implementation	Simulation	[78]
10.	LoShu configuration	9×9	SW, LW, LN, SN	Moderate	Number of relocation steps are minimum, implementation is economical, less flexible.	Simulation	[79,80]
11.	Futoshiki configuration	5×5	SW, SN, LW, LN	moderate	Unique solution, for m≠n array is not applicable.	Simulation/ Experimental	[81–83]
12.	Magic Square technique	3×3	SW, SN, LW, LN	Low	Power loss is minimum, module of first column is fixed.	Simulation/ Experimental	[84–93]
13.	Dominance Square Algorithm	5×5	SN, SW, LW, LN, non-continuous case, descending case, midpoint case	High	Limits the difference in row current; inappropriate for huge PV.	Simulation	[94]
14.	Square Arrangement Algorithm	3×3, 5×5	SW, SN, LW, LN	Moderate	Minimizes voltage and current loss; Insufficient for huge PV.	Simulation	[88]
15.	Ladder configuration	6×6	Vertical horizontal diagonal shading pattern	High	Compare to TCT, smaller number of cross-ties.	Simulation	[95–98]
16.	Two phase array reconfiguration algorithm	9×9	SW, SN, LW, LN	Moderate	Simple methodology; large power enhancement; comprehensive computation	Simulation	[26]
17.	Skyscraper Puzzle algorithm	9×9, 5×5	Non-homogenous row and column	Low	Wire loss is lower than Sudoku, no sensors and switches are required, relocation rules are complex.	Simulation	[99–103]
18.	Chaotic Baker Map Algorithm	4×4, 6×6	SW, SN, LN	High	Smaller scale, Shading dispersion is poor.	Experimental	[104–108]
19.	Ramanujan Reconfiguration	4×4	SN, SW, LN, LW	Low	Effective Shading Mitigation, Cable Losses	Simulation/ Experimental	[161]
20.	Arnold's CAT Map	4×4	100 shading conditions	Moderate	Wide Applicability and Experimental Validation	Simulation/ Experimental	[162]
21.	Cross Kit Reconfiguration	6×6	Dwarf Broad Shading Situation (DBSS), Tall Broad Shading Situation (TBSS), Shading state III: Dwarf Narrow Shading Situation (DNSS), Tall Narrow Shading Situation	High	Increased power output, reduced complexity	Simulation/ Experimental	[163]

(*Continued*)

Table 1. (Continued).

S. No.	Reconfiguration Strategies	Array Size	Type of shadow	Complexity	Merit/Demerit	Validation	Ref.
22.	ADdoku	9×9	SL, SW, LN, LS	Moderate	Simple Implementation and Scalability	Simulation	[60]
23.	Knight's Tour	9×9, 8×7, 8×14	SL, SW, LN, LS	Moderate	Simplicity and Scalability	Simulation	[101]
24.	Improved Odd Even Prime	9×9, 8×9	Top-Left, Top-Right, Bottom-Left, Bottom Right, Top-Left, Bottom-Right	Moderate	Enhanced Power Output Under Shading	Simulation	[164]
25.	Hyper Soduku	9×9	lower right, lower left corner, upper right corner, upper left, diagonal	Low	Potential for Large-Scale Applications	Simulation	[165]
26.	Recursive Addition Method	5×5, 9×9	SN, SW, LW, Random	moderate	Limited Applicability to Array Sizes	Simulation/ Experimental	[166]
27.	Black Widow reconfiguration	2×4, 5×5, and 9×9	Validation in OPAL-RT platform	High	Potential for Improved Performance	Experimental	[167]
28.	Zero switch and sensorless reconfiguration	4×4, 4×3	6 shading pattern	Moderate	Easily implemented and cost effective, limited validations.	Experimental	[168]
29.	Genetic Algorithm and two main reconfigurable steps based on a Switching Matrix (GA-2SSM)	9×9, 6×6, 12×12, 18×9, 18×18, 12×24, 30×48	4 shading pattern cases	Low to Moderate	Scalability and Cost-Effectiveness	Simulation	[120]
30.	Ancient Chinese magic square	9×9	4 shading profile with non-uniform irradiation level	Moderate	Improved Power Output and Shade Dispersion, Scalability	Simulation/ Experimental	[93]
31.	Two-step Reconfiguration	10×10	SN, SW, LN, LW	High	Reduced Complexity Compared to Traditional Methods	Simulation	[169]
32.	Novel prime number based PV array reconfiguration	9×9, 23×23	9 shading patterns	Moderate	Scalability and Simplicity, one time arrangement.	Simulation	[94]
33.	Regularized Deep Neural Networks	5×5	SW, SN, LW, LN	Moderate	Scalability and reduced complexity	Simulation	[170]
34.	Dimension-Independent Array Relocation (DIAR)	6×3, 5×7, 20×4, and 4×3	8 shading patterns	High	Wide Applicability and Simplicity	Experimental	[171]
35.	Static SDP Technique	3×3	SN, SW, LN, LW	Low	Simplicity and Low Cost, but Limited Adaptability to Different Shading Patterns	Simulation	[172]
36.	Automatic Column Wiring Resistance Algorithm	6×6	6 shading pattern	Moderate	Improved Performance Analysis, but Lack of Experimental Validation	Simulation	[173]
37.	Improved non-symmetrical puzzle reconfiguration	9×9	6 shading patterns	Moderate	Simple and Efficient Design, Limited Validation for Large Arrays	Simulation	[71]
38.	Generalized cryptographic image processing approaches	9×9, 5×10	24 distinct shading conditions	Moderate to high	Simplified MPPT Control, Improved Power Output Under Shading	Simulation/ Experimental	[174]

Table 2. Comparison of various dynamic PV reconfiguration strategies.

S. No.	Reconfiguration Strategies	Array Size	Type of shadow	Complexity	Merit/Demerit	Validation	Ref.
1.	Irradiation Equivalence by Relocation of Panels	3×3	Random	Moderate	Performance is high, switching action is less	Simulation	[17,112–115]
2.	Dynamic Electrical Scheme	9×9	Random	High	Large no. of switches required, each module is utilized	Simulation	[37,116–119]
3.	Electrical Array Reconfiguration	6×4	Single row, double row	Moderate	Minimum algorithm complexity	Simulation/Experimental	[120–124]
4.	Munkres algorithm	3×3	Typical type	Low	Simple procedures; low convergence speed; prolong service life.	Simulation	[37]
5.	Marine Predator Algorithm	9×9, 16×16, 25×25	SW, LW	High	Speed for convergence is high, search mechanism is tough	Simulation	[125–129]
6.	Butterfly Optimization Algorithm	6×4	Step by step row and column	High	Controlling parameters are less, speed for calculation is high	Simulation	[130–132]
7.	Water cycle Algorithm	10×10	Single row and double row partial shading	Moderate	Time for execution is minimum, unsuitable for real time	Simulation	[133–136]
8.	Gravitational Search Algorithm	6×4	Single row, double row, quarter	High	Can be easily trapped in local optima, convergence is low	Simulation	[137–139]
9.	Grey Wolf Optimization Algorithm	9×9	Non-uniform row shadowing, corner shadowing, non-uniform row column	High	Mismatch loss is reduced, search mechanism is complicated	Simulation	[140–143]
10.	PSO	9×9	SW, LN	Low	Great shade dispersion; robust; Local optimum is simple to trap.	Simulation	[144,145]
11.	Grasshopper optimization algorithm	9×9	SW, SN, LW, LN	High	Reliable and effective; bigger computational data.	Simulation	[146]
12.	Modified Harris Hawk optimizer algorithm	9×9, 6×4, 6×20	SW, SN, LW, LN	Moderate	Good performance all around; complicated search mechanism.	Simulation	[39,147]
13.	Artificial Ecosystem based algorithm	9×9	SW, SN, LN	Moderate	Output power is enhanced, convergence speed is high	Simulation	[148–151]
14.	Machine Learning Algorithm	4×3	Typical type	High	Poorly distributed shadow; based on machine learning; very slow convergence.	Simulation/Experimental	[152]
15.	Clonal Search Algorithm	4×4	Typical type	High	Power and money efficiency are both considered; challenging search methods.	Simulation	[153,154]
16.	Adaptive Array Reconfiguration	6×6	Random	High	Boost the amount of energy produced, losses due to mismatching are minimized, extra sensors and switches are needed for the massive adaptive component	Simulation/Experimental	[32,132,155–157]
17.	Bubble Sort Algorithm	3×3	Typical type	High	Excellent distribution of shade; Requires a large number of switches	Experimental	[158]
18.	Configuration Scanning Algorithm	3×4	Typical type	High	It is only necessary to have the short circuit current of the adaptive section, but this requires numerous computational steps.	Simulation	[22]
19.	Reconfiguration based on selection	3×3, 4×4	SW, SN, LW, LN	Moderate	Reduce the difference from the specified voltage; inadequate distribution of shade.	Simulation/Experimental	[159]

(*Continued*)

Table 2. (Continued).

S. No.	Reconfiguration Strategies	Array Size	Type of shadow	Complexity	Merit/Demerit	Validation	Ref.
20.	Power comparison algorithm	3×3, 4×4, 12×12	Typical type	Low	The methodology is simple, but it results in insufficient improvement in power.	Simulation	[160]
21.	Current Injection Reconfiguration	4×3	3 shading cases	Moderate	Reduced MPPT Complexity	Simulation	[127]
22.	Maximum-Minimum Tier Equalization Swapping (MM-TES) algorithm	3×3	Static oblique, random,	High	Wide Applicability and Experimental Validation	Simulation/Experimental	[175]
23.	Socio-Inspired Democratic Political (SI-DPA)	10×10, 15×15 20×20	uneven row; uneven column; SW; LW; SN; LN	Moderate	Potential for Efficiency and Speed	Simulation	[176]
24.	Atom Search Optimization (ASO)	9×9	shadow of moving clouds	Moderate	Improved Efficiency and Performance	Simulation/Experimental	[177]
25.	One-Step Adaptive Reconfiguration (1S-ADR)	4×4	SN, LN, SW, LW Random RA Symbol plus SY Letter C LC	Moderate	Scalability to Different Array Sizes	Simulation/Experimental	[178]
26.	Optimal Mileage using Swarm Reinforcement Learning (OM-SRL)	10×10	Continuous varying PSC, discrete varying PSC	Moderate	Improved Efficiency and Reduced Complexity	Simulation/Experimental	[179]
27.	Dragonfly Optimization Algorithm (DFO)	3×3, 9×9, 9×3	Three shading cases	Moderate	Reduced Complexity and Scalability	Simulation/Experimental	[180]
28.	Adaptive Evolutionary Jellyfish Search (AEJFS)	15×15	10 shadows	Moderate	Improved power output and adaptability	Simulation/Experimental	[181]
29.	Firefly Algorithm Reconfiguration” (FFA)	3×3, 5×5	Downward Ladder, L Shape, Quadra Corner, Random A, Tetris Shape, Triangle Shape, Two Side Corner, U Shape, X Shape, X (500)	Low	Potentially Simple and Fast Algorithm, but Software-Based Validation Only	Simulation	[182]
30.	Conquer Q-Learning (DCQL) algorithm	9×9	SW, SN, LN, LW	High	Improved efficiency but computational complexity	Simulation/Experimental	[183]
31.	Dynamic Leader based Collective Intelligence (DL-CI)	9×9	10 cases of PSCs	Moderate	Enhanced Global Search and Local Exploration, Computational Complexity and Parameter Tuning	Simulation/Experimental	[184]
32.	Swarm based Double Q-learning (S-DQL)	10×10	Continuous and discrete varying PSC	Moderate	Reduced Power Fluctuation and Cost	Simulation	[185]
33.	Followed The Regularized Leader (FTRL) model reconfiguration	4×4	3 shading patterns for different timing.	Moderate	Easy to implement and less costly.	Experimental	[186]
34.	Fuzzy Logic and Recursive Least Squares Based Reconfiguration	4×4	8 shading patterns	Moderate	Reduced Investment Cost	Experimental	[187]

(*Continued*)

Table 2. (Continued).

S. No.	Reconfiguration Strategies	Array Size	Type of shadow	Complexity	Merit/Demerit	Validation	Ref.
35.	Harmony Search	5×5, 9×9, 9×5, 3×3	12 shading patterns	High	Faster Convergence and Reduced Complexity	Experimental	[188]
36.	Evolutionary based Pareto Optimization Algorithms	10×10, 15×15, 20×20	LN, LW, SN, SW	Moderate	Versatility with Multiple Algorithms	Simulation	[189]
37.	Scan Pattern	9×9, 8×8, 4×4, and unsymmetrical 8×6	34 distinct shading cases	Moderate	Wide Applicability and Implementation Advantages	Experimental	[190]
38.	Seagull Optimization Algorithm (SOA)	9×9	LN, LW, SN, SW	Moderate	Effective Shading Pattern Handling	Simulation	[191]
39.	Hybrid Red Deer with Moth Flame Optimization	9×9	4 shade patterns	Moderate	Potential for Large-Scale Arrays	Simulation	[192]
40.	Artificial Rabbit Optimization (ARO)	4×4, 20×15	Random	Moderate	Modular Design and Cost Reduction	Simulation/Experimental	[193]

situations, making them extremely efficient for maximizing energy production. The dynamic approaches' capacity to continuously adapt settings in real-time leads to substantial enhancements in overall efficiency and energy acquisition. Ultimately, although static reconfiguration methods have the benefits of being simple and having lower starting costs, dynamic reconfiguration approaches are more desirable due to their capacity to adapt and improve performance in reducing the impact of partial shading. Future research and developments in technology have the potential to further decrease the expenses and intricacy linked to dynamic reconfiguration, hence expanding their usefulness and efficiency in the management of photovoltaic arrays.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Vaishali Gautam is currently pursuing her PhD from Electrical Engineering Department, Jamia Millia Islamia. She obtained her M. Tech from Jamia Millia Islamia in Electrical Engineering in the year 2020. She did her B. Tech from IERT, Allahabad in Electrical Engineering in the year 2016. She has published several research papers in reputed Journals and Conferences. Her research interest include Renewable energy technology, PV systems and partial shading conditions.

Shahida Khatoon started her career in 1992 as an assistant professor, then got promoted to associate professor in 2009, and professor in the department of electrical engineering, JMI, in 2011. She has done B. Tech (Electrical Engineering) in 1990 from JMI, M. Tech in 1995 from IIT Delhi, then Ph.D. from JMI in 2004. She was conferred the prestigious All India Council of Technical Education (AICTE) Award for Young Teachers in 2008. She has also worked at AT & T Bell Lab, New Jersey, USA in 2004. She has guided ten Ph.D.'s. She has published 25 research papers in journals of repute and 83 papers in national and international conferences. She has also contributed to the corporate life of the university, worked as deputy Provost from 2003 to 2008. Her research interests include electric power systems and renewable energy systems.

Mohd Faisal Jalil has more than 12 years of teaching and research experience. He is a Senior Member of IEEE. Currently, he is working as an Assistant Professor in the Electrical Engineering department, Aligarh Muslim University, Aligarh, India. He has also served as Assistant Professor at KIET Group of Institutions, Delhi-NCR, Ghaziabad, India, during 2013–2021. He received his Ph.D. From the Electrical engineering department, Jamia Millia Islamia (JMI), New Delhi, India. He obtained his B. Tech and M. Tech from the Electrical Engineering department, Aligarh Muslim University, Aligarh, India, in 2010 and 2012, respectively. He has published several research papers in reputed journals and conferences. His research interests include electrical machines, renewable energy systems, and PV systems under partial shading conditions.

R. C. Bansal has more than 25 years of teaching, research, academic leadership, and industrial experience. Currently, he is a Professor in EE Department, University of Sharjah (UAE). In previous postings, he was Professor and Group head (Power) in EEC Department, University of Pretoria (South Africa) and worked with the University of Queensland (Australia); University of the South Pacific (Fiji); BITS Pilani (India); and Civil Construction Wing, All India Radio. Prof. Bansal has published over 500 journal articles, conference papers, books, books chapters. He has Google citations of 21,000 and h-index 70. He has supervised 25 Ph.D. and 5 Post Docs. He is an Editor/AE of IEEE Systems Journal, Smart Grids and Sust. Energy, and Electric Power Comp. and Systems. He is a Fellow, and CP Engg IET-UK, and Fellow Institution of Engineers (India). His research interests include renewable energy, power systems, and smart grid.

ORCID

R. C. Bansal http://orcid.org/0000-0002-1725-2648

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