Dynamic Reconfiguration of PV Array under Partial Shading Condition by Using Automatic Switching

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***Abstract*—The mismatching effect caused by partial shade is one of the critical problems in the operation of photovoltaic (PV) arrays, it can cause large losses in the power produced by the PV system. Power losses due to Partial Shading (PS) for a particular operating situation may be controlled by altering the PV array's scheme connection. For that reason, this paper presents an Automatic Switch Block (ASB) based on dynamic relays without using an algorithm to control the connection between PV panels to reduce the effect of partial shading and provide the ability of scaling. The Simulation results showed that the proposed module has a high ability and efficiency in mitigating and reducing the effect of partial shade on solar panel arrays by automatically changing the electrical connection between the panels compared with Total Cross-Tied (TCT), Futoshiki Puzzle Pattern (FPP), Sudoku and L-Shape Algorithm. Moreover, the proposed method was tested in SIMULINK/MATLAB environment for different shading patterns and achieved an improvement in Maximum Power Point Tracking (MPPT) by about 12% as compared with L-Shape, more than 30% compared to TCT, and about 15% for other methods.**

***Index Terms*—Dynamic PV array reconfiguration, panels array, partial shadow, shading patterns, solar energy**

I. Introduction

In recent years, the world has tended to find ways to obtain sustainable sources of energy as an alternative to traditional energy sources. Among the methods that scientists have reached is to take advantage of sunlight to generate energy, including manufacturing solar panels [1, 2]. But many factors may impact the capacity of the panels and decrease the maximum output power, including partial shade due to clouds, dust, nearby buildings, etc. [3]. This led researchers to find appropriate solutions to avoid the effects resulting from partial shade. Methods for rearranging solar panels are generally divided into static and dynamic methods [4, 5]. In a static configuration, the physical placement of the module is changed without affecting the electrical connections, according to a pre-defined one-time configuration scheme. As a result, the impact of partial shading is distributed over the full photovoltaic (PV) array [6]. Consequently, the static interconnection strategy does not require sophisticated algorithms, switching matrices, or auxiliary circuits such as Sudoku [7], Optimal Sudoku [8], Futoshiki [9], Odd-Even (OE) [10], Latin Square (LS) [11] and magic square [12]. As all the fixed techniques rely on a single reconfiguration and the use of a mechanical mechanism to alter the placement of the solar panels, they are ineffective and do not address various partial shade patterns, most of them find it difficult to deal with the system's expansion [13]. However, the dynamic methods are more effective in dealing with reducing the effect of partial shade by reconnecting the electrical connections between the solar panels, depending on Artificial Intelligence (AI), neural networks, and fuzzy logic, using different algorithms to resolve the problem of maximum power point tracking (MPPT) [14]. In case the issue of system expansion and the effectiveness of techniques to extract the highest value of capacity while using the fewest number of switches remain in the study stage [15].

II. Literature Review

This section reviews the methods and studies that use the dynamic method to solve the partial shading issue. Srinivasan *et al.* [16] present in their study an algorithm called L-shape to solve the problem of expansion which both Sudoku and Futoshiki failed in non-square matrices. The Sudoku and Futoshiki PV array patterns are only relevant to square PV arrays, and their logic fails for arrays that are not square. The suggested method is optimal for both non-squared PV arrays with an odd number of columns and squared PV arrays. For the non-squared array of PVs with an even number of columns. However, the proposed hybrid reconfiguration method is evaluated against eight different shading patterns, with methods like Total Cross-Tied (TCT), the Sudoku puzzle pattern, and the Futoshiki Puzzle Pattern (FPP). According to the findings, the suggested approach produced the following outcomes, the error rate is 20% in the current method compared to the Sudoku and Futoshiki methods, which was 35%. However, the

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implication is that the current configurations work well for minor shading patterns but fail paltry for major shading patterns. Hegazy Rezk *et al*. [17] described a modern metaheuristic method that uses the Coyote Optimization Algorithm (COA) to solve the reconfiguration of a partially shaded PV array. The primary objective is to increase the Global Maximum Power (GMP) of the array. The suggested COA is implemented on (99) PV panels. The COA has been evaluated using a variety of conventional shadow patterns, like a Short Wide (SW), Long Wide (LW), Short Narrow (SN), and Long Narrow (LN). The recommended COA-based designs are compared to TCT, Sudoku, Flower Pollination Algorithm (FPA), Marine Predators' Algorithm (MPA), and Butterfly Optimization Algorithm (BOA)-based configurations. The optimal increase in GMP attained with the suggested COA for TCT configuration is 26.58% in the SW case, 21.69% in the LW, 7.68% in the SN, and 7.69% in the LN. The accumulated results verified the competence and superiority of the recommended COA in reconfiguring the shaded array. In [18], the authors provided a method based on the Knapsack algorithm, while the reconfiguration issue is formulated as a 0-1 multi-knapsack problem, and a unique mathematical formula is devised. The development of a model that directly estimates the maximum output power of a solar array. By solving the mathematical model afterward, the ideal reconfiguration technique is identified. The efficiency of the suggested reconfiguration module is shown through theory and simulations. In conclusion, the suggested pattern technique may successfully optimize the maximum output power of a PV array, with a power gain of more than 10% observed for the previously mentioned shading conditions when compared to the baseline TCT configuration and the Irradiance Equalization (IE) based reconfiguration strategy. Moreover, exhaustive simulations demonstrate that the proposed method's maximum output power is always larger than or equal to that of the IE principle, regardless of the size and shading pattern of the PV array. The researchers in [19] and [20] proposed techniques to limit the number of peaks in the power curve and to remove the aging effect that could occur to the panels because of the sparse shade in one row. The study was conducted in a simulation environment and compared with various approaches and matrices of varying sizes, with the results module that the suggested algorithms are able to improve output power and reduce the number of peaks when compared to standard methods. Authors in [21] and [22] proposed a module based on fuzzy logic to extract MPPT, where the dependence is on tracking the suitable voltages by changing the connection between the panels from series to parallel or parallel to series, and it was compared to the traditional method (TCT). It was claimed to be superior. The proposed methods extract the relevant voltage to produce the MPPT faster. Authors in [23] and [24] proposed algorithms based on Perturb and Observe (PO) technology, which scans a curve (I-V) to determine a maximum power point and then separates the shaded panels in the system's rows, with the results demonstrating that it has higher accuracy, faster, and less complicated by 2 times to 3 times. In comparison to the other three major algorithms, Maximum Information Coefficient (MIC), Source Coherence (CS), and ACO-PO, to improve the performance under the influence of partial shade, some researchers used a neural network. Tuyen Nguyen-Duc *et al*. [25] proposed the reconfiguration method to be based on equalizing short-circuit current reduction of the PV matrix in the solar panel's system. To estimate the effect of partial shading, eight cutting-edge convolutional neural network models are used on PV modules short-circuit current LeNet-5, AlexNet, VGG 11, VGG 19, Inception V3, ResNet 18, ResNet 34, and ResNet 50 are among these approaches. Based on 1842 sample images, the VGG 19 achieves the largest accuracy among the eight models. As a result, in four different shading scenarios, this approach is used to evaluate the ratio between the actual and estimated short-circuit currents. Under Partial Shading Condition (PSC), this ratio establishes the rule for switching between PV modules across the PV panels. In four shading patterns, the experimental PV array with a size of (2×2) approaches the suggested pattern module and increases output power by 25.19 percent. Consequently, power losses decreased from 1.32 to 13.75 percent. The proposed dynamic PV array reconfiguration system's power reduction with the improvement of power loss proves its efficacy in mitigating the impacts of PSC on the PV panels in four shading case studies. Moreover, this study proposes an automatic dynamic reconfiguration approach. It does not need a standard programmable microcontroller. Instead, it immediately adjusts the connections between PV modules based on their activity, which is influenced by the shade situation to facilitate scalability.

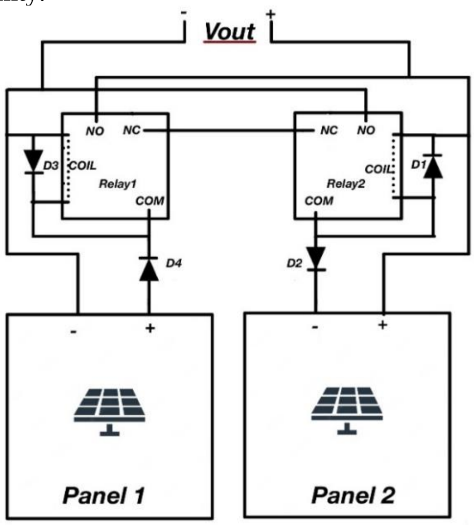


Fig. 1. Automatic switching block (ASB)

III. Proposed Method

An automatic dynamic reconfiguration scheme is proposed in this paper. It circumvents the need for a conventional programmable microcontroller. Instead, it updates the interconnection among PV modules directly according to the activity of PV modules that are affected by the shading condition. For ease of scalability, a hierarchical structure is used to construct the PV array from a modular building block, called the Automatic Switching Block (ASB). As shown in Fig. 1. This ASB connects two PV panels or groups of panels. It is designed such that when there is partial shading it can automatically change the connection between the two PV panels to achieve the target of output voltage stability.

The PV panels are connected through relays that are controlled by the generated voltages to produce a nearly constant output voltage as much as possible. The two PV panels are supposed to generate equal output voltages at no shading (normal) conditions, i.e., $E_1 = E_2$, where E_1 and E_2 are the output voltages of PV_1 and PV_2 respectively. A Panel is considered as shaded when its output voltage falls down under a predefined threshold, e.g., 50% of its maximum output. The used relays are calibrated such that they switch from Normally Closed (NC) to Normally Open (NO) states when the coil voltage exceeds this threshold.

The proposed system operates as follows, at normal operating conditions when both PV panels are receiving almost equal solar irradiation, their output will force the relays to connect them in parallel. Then, both voltages with current at the output of the block are in Eqs. (1, 2), where I_1 and I_2 represent the current for PV_1 and PV_2.

$$E_{\text{block}} = E_1 = E_2 \tag{1}$$

$$I_{\text{block}} = I_1 + I_2 \tag{2}$$

Next, in the case when one of the PV panels is shaded and its output falls while the other panel is still producing a normal output, then the designed connection scheme disconnects the weak (shaded) panel. As the difference in solar irradiance received by the two PV panels increases, it causes a significant mismatch in the current-voltage (*I-V*) characteristics that make the weak panel act as an electrical load on the non-shaded panel. This leads to significant power loss and early panel aging, so it is better to be avoided. Therefore, in this case, the block output is taken from the non-shaded panel alone to protect the weak panel and to maintain a constant block output voltage level, That is, $E_{\text{block}}=E_i$ and $I_{\text{block}}=I_i$, where i is the index of the non-shaded panel and $i\in\{1,2\}$. Finally, the remaining case is when both PV panels are shaded. Then, the relays will connect the weak panels in series. In this case, the output voltage and the output current will be as in Eq. (3) and Eq. (4):

$$E_{\text{block}} = E_1 + E_2 \tag{3}$$

$$I_{\text{block}} = I_1 = I_2 \tag{4}$$

The operation of the proposed modular ASB block is summarized in Table I.

TABLE I: OPERATION OF THE PROPOSED MODULAR ASB

Shading condition		Type of connection		Output Voltage
PV 1	PV 2	PV 1	PV 2	
NO	NO	Parallel		E1//E2
NO	YES	PV1 only		E1
YES	NO	PV2 only		E2
YES	YES	Series		E1+E2

Typically, flyback (or freewheeling) diodes D1 and D3 in Fig. 1, are used in printed circuit boards that include mechanical relays. A freewheeling diode is installed with opposite polarity from the PV panel's output and in parallel with the inductance coil of the relay. A flyback diode prevents high voltage spikes from occurring upon disconnection of the PV. In other words, when the PV panel is connected to the relay, the voltage of the inductance coil increases until it matches that of the power source.

The inductor's time constant restricts the rate at which the current may fluctuate. In this instance, the time required to reduce current flow via the coil exceeds the time required to remove the PV panel. In an effort to maintain current flow, the inductive load in the coil switches polarity upon separation. This causes a high voltage potential to accumulate at the open connections of the component that controls the relay. It may cause an electrical arc and harm the relay's regulating components. Additionally, it may produce electrical noise that can couple with nearby signals or power connections and cause microcontrollers to fail or reset. In addition to flyback diodes, the designed ASB features two blocking diodes, D2 and D4. They prevent the flow of reverse currents through weak PV panels. However, they are forward biased, and this results in an about 0.7V drop in the voltage delivered by each PV panel. Moreover, PV arrays can be constructed by connecting ASB blocks hierarchically. This structure allows easy and effective scaling. That is a 4-PV panel array can be constructed by applying the proposed ASB connection scheme on each pair of PV panels. However, Fig. 2 shows 8-PV panel arrays. For the case of an 8-PV panel array, four ASB blocks are used to connect each one of the four pairs of PV panels, and the output of pairs connected in parallel, the same approach can also be followed to form a matrix of 16 PV panels or greater.

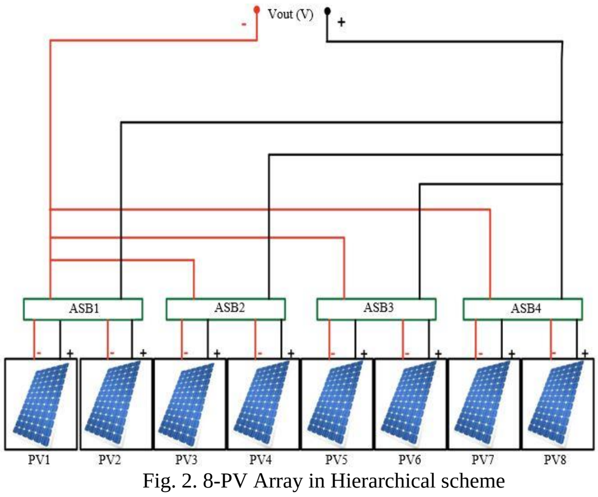


Fig. 2. 8-PV Array in Hierarchical scheme

For calculating the total current (I_{Total}) and voltage (V_{Total}) at the output of the PV panel, the array (4×4) matrix in case of no shading will be as in Eq. (5) for total output current and as in Eq. (6) for total output voltage.

$$I_{\text{Total}} = I_{\text{PV1}} + I_{\text{PV2}} + \cdots + I_{\text{PV16}} \tag{5}$$

$$V_{\text{Total}} = V_{\text{PV1}} = V_{\text{PV2}} = \cdots = V_{\text{PV16}} \tag{6}$$

Based on this principle, taking into consideration the condition of the PS on a particular panel, the current and voltage are evaluated by considering the state of connection between two panels in the group, for example, if Panel 2 had a radiation ratio of less than 50%, it will be eliminated from the equation.

IV. Results and Discussions

The proposed ASB-based hierarchical scheme is applied on a sixteen PV panel array (4×4) matrix. The array has been implemented in SIMULINK/MATLAB environment by using 10W PV panels and eight ASB modules. The specifications of the PV panels used as given in Table II.

TABLE II: PV Panels Properties

Parameter	Value
Power (W)	10
Short circuit current (A), ISC	1.25
Current at MPP (A), I_m	1.1
Voltage at MPP (V), V_m	9
Open Circuit Voltage (V), VOC	10.8

TABLE III: PS Patterns and Maximum Power Point Tracking of the ASB-based Hierarchical 16-PV Panel Array

Shading patterns	Maximum Output Power (Watt)				
	TCT	Sudoku	FPP	L-Shape	ASB Configuration
Short Narrow	84	97.4	102.5	102.5	120.6
Short Wide	65.5	58.8	65.5	90.7	87.3
Long Wide	53.8	65.5	58.8	73.9	70.26
Long Narrow	60.5	77.3	84	92.4	100
Uneven Column	67.2	102.5	102.5	102.5	120.6
Uneven Row	102.5	102.5	102.5	102.5	118.7
Random	60.5	47	53.9	73.9	76.2
Diagonal	102.5	73.9	97.4	102.5	120.4

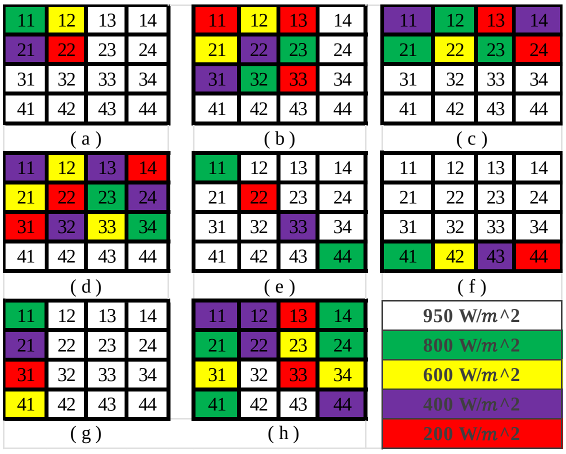


Fig. 3. Shading patterns with different Irradiance values [16]: (a) SN, (b) SW, (c) LW, (d) LN, (e) diagonal (f) UN column, (g) UN Row, and (h) random.

Without loss of generality, the sixteen PV panels are arranged in a single row. However, the PV panels may encounter different shading patterns. As mentioned in the methodology, a PV panel is considered shaded if its output falls under the predefined threshold, otherwise, it is considered not shaded. Then, basically, there are different possible shading conditions like a standard pattern: LW, LN, SW, and SN in addition to non-standard patterns: Diagonal, Uneven Row, Uneven Column, and Random. However, Table III shows tested shading cases, with different values (800, 600, 400, 200, and 950 for no shading panels with colors Green, Yellow, Purple, Red, and no color for unshaded panels) to track MPPT as shown in Fig. 3. Moreover, the results of ASB method will be compared with the results in reference [16].

A. *Performance Analysis Under Standard Cases*

1) *Short & Narrow Case*

A case of SN shading pattern may happen in the PV array because of surrounding objects covering 25% of the PV array size. The shading in SN has affected the panels (11, 12, 21, 22) in the matrix as shown in Fig. 3 The simulation result showed that the value of MPPT was higher in ASB configuration 120.6 W followed by L-shape and FPP 102.5 W in case TCT and Sudoku was recorded 84 W, 97.4 W at the maximum point, however, ABS reconfiguration has 12.15% improvement compared to L-shape and FTT beside 24.58% compare with TCT and 15.58 with Sudoku. Fig. 4, shows the P-V characteristic for each method.

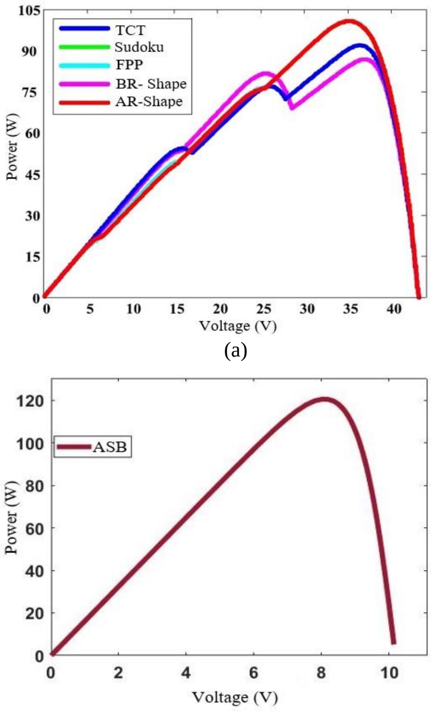
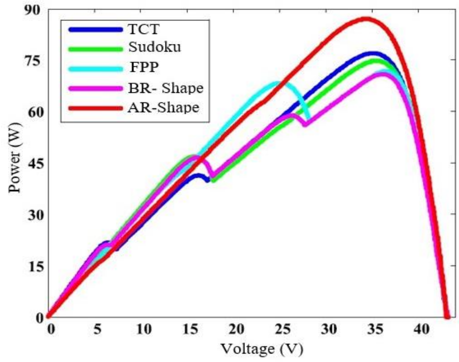


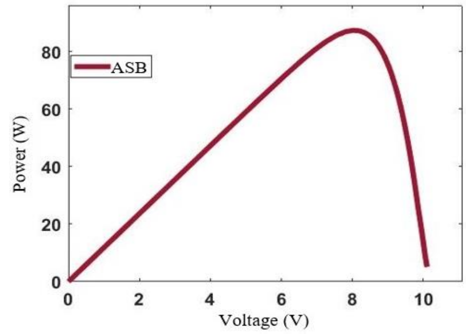
Fig. 4. P-V characteristics for SN case: (a) TCT, Sudoku, FPP, and L-Shape [16] and (b) ASB reconfiguration.

2) *Short & Wide Case*

This subsection discusses the shading dispersion under SW shading patterns. 75% of the PV area is affected by this kind of shade as shown in Fig. 3, because of the considerable power loss, shadow dispersion is critical for this shading situation. Shade dispersion may increase power in this type of shading. However, it is dependent on consistency. The suggested reconfiguration approach evenly distributes shadowing throughout the PV array beside the L-Shape configuration with a slight difference not exceeding 2% where the amount of MPPT achieved is 87.3W for ASB and 90.7W for L-shape compared with standard patterns like TCT and FPP with the value of 65.5W. However, the Sudoku pattern achieved the lowest value with only 58.8W. P-V characteristics are shown in Fig. 5, for each method.

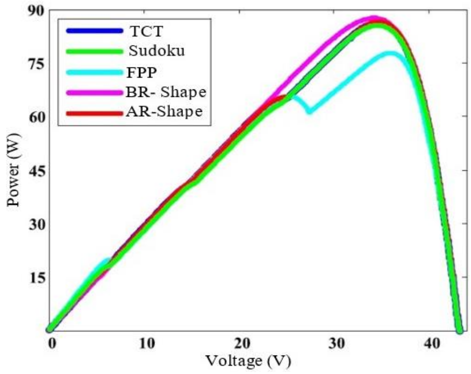


(a)

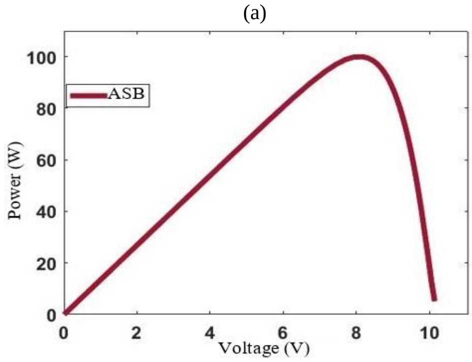


(b)

Fig. 5. P-V characteristics for SW case (a) TCT, Sudoku, FPP, and L-Shape [16] and (b) ASB reconfiguration.



(a)



(b)

Fig. 6. P-V characteristics for LN case (a) TCT, Sudoku, FPP, and L-Shape [16] and (b) ASB reconfiguration.

3) *Long & Narrow Case*

A case of LN shading pattern reduces the irradiance of the PV array by about 50%, resulting in a 50% reduction in power output. For this kind of shading pattern, the recommended ASB reconfiguration is more effective. As shown in Table III this configuration could achieve 100 W followed by L-shape, FPP, Sudoku, and TCT by 92.4 W, 84W, 77.3W, and 60.5W. However, the proposed reconfiguration is better than TCT, Sudoku, FPP, and L-shape by 26.56%, 15.24%, 10.74%, and 5.1% as shown in Fig. 6.

4) *Long & Wide Case*

In the case of LW shading condition influences around 75% of the PV array's irradiance. This type of shadowing is typically caused by clouds, impassable obstacles, and temporary constructions, however. Besides the L-shape method, the recommended reconfiguration strategy uniformly distributes shadowing across the PV array with a little variance not exceeding 2% as shown in Fig. 7, where the quantity of MPPT produced is 70.26 W for ASB configuration and 73.26 W for L-shape configuration in case TCT and FPP record lowest value with only 58.8 W and 65.5 W for Sudoku as in Table III. Fig. 8 shows the characteristics of P-V.

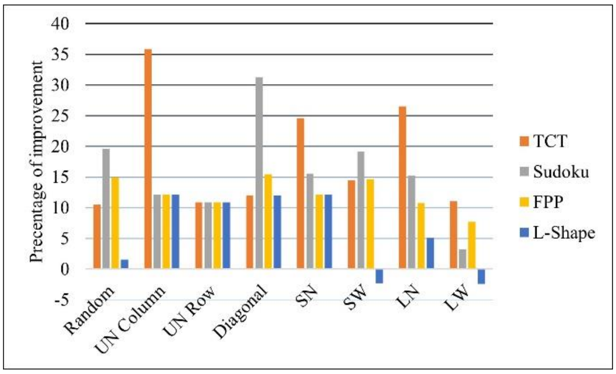
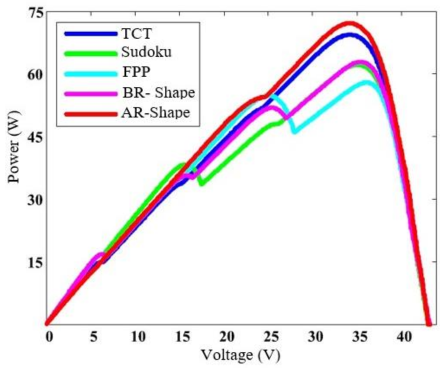
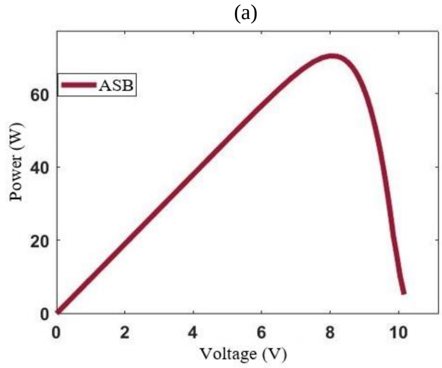


Fig. 7. Improvement percentage of ASB configuration compare with TCT, Sudoku, FPP, and L-shape configurations.



(a)



(b)

Fig. 8. P-V characteristics for LW case (a) TCT, Sudoku, FPP, and L-Shape [16] and (b) ASB reconfiguration.

B. *Performance Analysis Under Non-Standard Cases*

In a non-standard shading pattern, due to the shape of the PV array in a square or rectangular matrix shape, it may get a shadow from surrounding higher, narrower objects such as towers, chimneys, or clouds, and environmental change. Therefore, different patterns were imposed to simulate these cases like Diagonal, Uneven Columns, Uneven Rows, and Random patterns. However, as shown in Table III the suggested configuration is more effective for these types of shadow cases. The percentage of improvement of the suggested pattern in the four situations indicated above is 12.15%, 12.02%, 10.88% and 1.54% for Uneven Column, Diagonal, Uneven Row and Random pattern compare with L-shape algorithm reconfiguration, in case the proposed pattern more effective compared to Sudoku, FPP and TCT in the random pattern by 19.61%, 14.97%, and 10.54%. However, Fig. 7 shows an improved percentage of ASB configuration compared with TCT, Sudoku, FPP, and L-shape configurations, as the *x*-axis represents the point of comparison between the proposed method and the other methods.

V. Conclusion

In this paper, an automatic switching scheme has been proposed to control the dynamic reconfiguration of a PV array subject to PS. An ASB module is designed to control the parallel or series connection of two PV panels. By connecting the ASB modules in a hierarchical manner, PV panels can be constructed. In contrast with conventional dynamic reconfiguration schemes, ASB-based PV arrays do not use programmable controllers and related hardware, therefore they are less complex. In addition, the hierarchical structure facilitates the ease of array scaling and ignores the need to redesign or modify the controller software, I/O ports, and switching matrix. The SIMULINK tests of the implemented 16-PV panel array under different PS conditions show the ability of the array to maintain an MPPT and be more effective compared with the methods L-shape, TCT, FPP, and Sudoku by over 12% in most cases. Whereas, in cases of wide and random shadows, they are close in result with an L-shape. Moreover, the ASB-based PV array requires a smaller number of switches (half the number of switches) as compared with an equivalent L-shape PV array. However, the array collects the currents produced by the PV panels under different shading conditions. Therefore, the total output current and power vary depending on the ability of panels to produce power.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The paper conceptualization, software simulation, formal analysis, resources, data curation, writing, and visualization have been done by Koran A. Namuq. The supervision, validation, investigation, methodology, project administration, and review-editing have been done by Abdulrahman I. Siddiq, and Hasan Abdulkader. All authors had approved the final version.

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