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Automatic PV Array Reconfiguration under Partial Shading Conditions

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ABSTRACT

Photovoltaic (PV) arrays have been established as one of the main sources of clean and renewable electricity. In practice, PV arrays are subject to unavoidable non-uniform partial shading (PS) due to clouds, buildings, dust, etc. PS causes the hot spot problem, mismatch losses, and output power degradation. A widely used approach to mitigate the effect of PS is dynamic reconfiguration, where, the interconnection of PV panels is modified according to the shading condition to achieve the maximum possible output. Dynamic reconfiguration techniques use sensors, programmable controllers, and switch matrices for optimal operation. However, they have drawbacks such as system complexity and scalability issues. For instance, reducing the number of switches limits the flexibility of the reconfiguration algorithm. In this paper, an automatic dynamic reconfiguration scheme is proposed in which PV panel irradiation activity controls the interconnection of PV panels. A modular building block comprised of relays and diodes is proposed and implemented. The building blocks can be used to interconnect PV arrays in a hierarchical manner. This approach nullifies the need for a programmable microcontroller and related circuitry which reduces complexity and cost. Also, the hierarchical design enables easy scaling and expansion. Experimental and analytic results have verified the effectiveness of the proposed reconfiguration scheme.

1. Introduction

Environmental concerns, increasing demand for energy driven by the ever-growing technologies, and an increasing world population require eco-friendly and efficient sources of energy. Photovoltaic (PV) solar energy generation continues to attract more attention as one of the main future sources of renewable energy [1].

Different issues can affect the efficiency of PV solar systems one of which is partial shading (PS), which occurs when an external object, such as a nearby building or trees, clouds, or dust, etc., obstruct the path of sunlight to the PV solar panel [2]. PV modules are connected in series and parallel combinations to design PV arrays. PS occurs when a PV cell/module or more becomes shaded while the others are still receiving normal irradiation. This leads to a serious reduction in the power generated by the entire system [1,2]. PS can also lead to damaging PV modules due to the formation of hot spots in shaded areas [2,3] if the issue is left without proper treatment.

There are different measures and techniques to mitigate the effects of PS. Bypass diodes can be connected across modules to mitigate the effects of PS and prevent the formation of hot spots. However, this can lead to shifting the voltage-current relationship of the module to a local maximum power point [4-7]. Different interconnection configurations can be used for connecting PV modules to form solar arrays, e.g., serial-parallel, total cross-tied (TCT), bridge linked, etc. Among these connection configurations, it was found that TCT exhibits higher tolerance to PS [6].

Reconfiguring the PV modules within an array is another technique to mitigate the effects of PS. Mainly, reconfiguration techniques can be classified into static and dynamic techniques. In static reconfiguration systems, the physical location of modules within the array is altered based on a configuration system designed a priori with the objective of distributing the effect of PS throughout the solar array. Different static configuration schemes have been designed and studied in the literature [6,8]. On the other hand, the most popular class of reconfiguration techniques is dynamic reconfiguration, where the interconnections of the modules dynamically change within the array according to the irradiance condition with the objective of increasing the produced power [5,6,8]. This technique requires monitoring the system with sensors, then the collected information is passed to an algorithm that solves a mathematical model in order to reach an optimized configuration which will be implemented through a switching system. Such systems can react to different irradiance conditions, however, they face scaling issues as the system size increases [8,9]. Adding or removing PV modules from the PV array requires significant modifications to the hardware of the control system and the heuristic reconfiguration algorithm. That is, a larger number of switches, sensors, and control strategies are required in dynamic reconfiguration as compared to other reconfiguration methods. Consequently, this imposes limitations on PV array scalability and limits this approach to small-scale installations [10,11]. Moreover, in spite of using microcontrollers and programmed reconfiguration algorithms, there is no heuristic reconfiguration algorithm yet known to be fully successful in producing the optimal solution under all different possible partial shading conditions [12,13].

Therefore, in this paper, an automatic dynamic PV array reconfiguration technique is proposed. It is designed to be able to reconfigure the connection of PV modules automatically depending on their activity without the use of microcontrollers and software reconfiguration algorithms. In order to facilitate the scalability of the PV array, a hierarchical structure is proposed with an elementary modular building block that allows automatic flexible and parallel-series reconfiguration of two PV panels.

The rest of the paper is organized as follows. In Section II a review of related works is presented. Then, the proposed automatic reconfiguration scheme is described in Section III. The analysis and experimental implementation of the proposed scheme are given in Section IV. Finally, Section V concludes the paper.

2. Literature Review

Topology adjustment in dynamic reconfiguration of PV modules is implemented under the control of programmed microcontrollers. The power generated by each PV panel is sensed and passed to the controller, which identifies the shading pattern. Then, according to a reconfiguration algorithm, the controller adapts the electrical structure of the PV array through a switching matrix with different approaches and goals [8]. This strategy is applied in [14,15] to maximize output power and maintain a constant output load voltage.

A significant part of the research in this field has been investigating the effect of the used heuristic reconfiguration algorithm on system performance [2,7,16-29]. Different reconfiguration and optimization techniques have been implemented which utilize mathematical calculations, artificial neural networks, genetic algorithms, fuzzy logic, etc.

Hybrid methods that combine the benefits of different reconfiguration algorithms have been considered in [18] and [33]. It is reported that hybrid algorithms can improve system performance in terms of output power, reconfiguration speed, and PV panel lifetime. Generally, these systems are relatively more complex since the implementation of hybrid algorithms is more complex than individual reconfiguration algorithms.

However, when more parameters on the specific partial shading condition are taken into consideration, then, the performance of the reconfiguration algorithm is expected to improve. In [31], the system is designed to differentiate between slow and fast moving partial shading. The system has less switching time and hardware requirements, but the results show that in some cases the controller may fail in distinguishing between different shading conditions, resulting in performance degradation.

Moreover, the economic benefits that are achieved from applying dynamic PV array reconfiguration under partial shading conditions have been studied in [1,20,33]. As an example, the experimental work in [1] shows that the amount of output power is affected by the position of aged PV modules. The repositioning of these modules can improve power production and avoid the cost of replacing them.

Dynamic reconfiguration is characterized by the requirement of a programmable controller and a relatively large number of switches [4,31-33]. In [4] the proposed reconfiguration technique uses a configuration of sensors and switches and shows that it is capable of dispersing a significant part of the imposed shading with the remaining shading effects being nearly nullified. Similarly, in [33], a dynamic reconfiguration scheme is proposed that uses double pole double throw switches. A direct conclusion is that, the fewer switches being used, the less flexible the system is to mitigate the effects of partial shading. Therefore, in this paper, it is proposed to keep the number of switches large enough to maintain the required reconfiguration flexibility while trying to reduce the system complexity by discarding the use of the programmable controller and replacing it with an automatic switching technique that depends directly on the activity of PV panels. Experimental tests show that the switch count of the proposed switching network is one-third and significantly less compared to conventional semiconductor switching networks. This can be considered a significant reduction in overall system complexity since the controller has to perform exhaustive calculations at each shade condition before it can determine suitable switching.

3. Proposed Reconfiguration Scheme

An automatic dynamic reconfiguration scheme is proposed in this paper. It eliminates 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 to form a modular building block, called the Automatic Switching Block (ASB). 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 objective of output voltage stability.

As shown in Figure 1, 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 under no shading (normal) conditions, i.e., $E_1 = E_2$, where E_1 and E_2 are the output voltages of PV1 and PV2, respectively. A PV panel is considered shaded when its output voltage falls below 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 drops below this threshold.

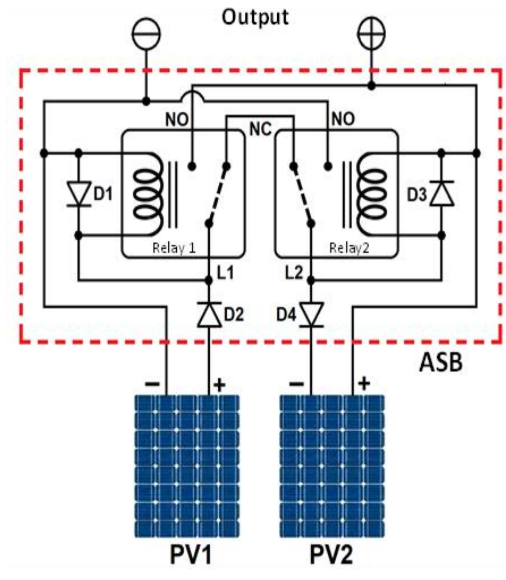


Figure 1: Automatic Switching Block

The proposed system operates as follows, at normal operation conditions when both PV panels are receiving almost equal solar irradiation; their output will signal the relays to connect them in parallel. Then, the output voltage and current of the block are $E_{block} = E_1 = E_2$ and $I_{block} = I_1 + I_2$. Next, in the case when one of the PV panels is shaded and its output falls below 50% of the maximum output while the other panel is still producing a normal output, then, the designed connection scheme disconnects the shaded panel. In practice, the overall output voltage of the parallel combination will be somewhere between the lower and higher panel voltages. At low output voltage levels this mismatch may not be a serious problem, but as the solar irradiance increases towards or beyond (1000 W/m^2) the mismatch in the current-voltage (I-V) characteristics of each PV panel can cause significant power loss and early panel aging, and it is better to be avoided. Therefore, in this case, the block output is taken

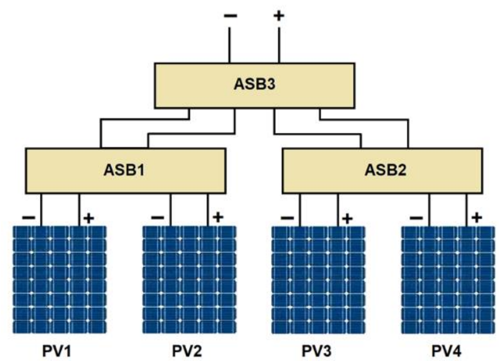
from the non-shaded panel alone to protect the panels and to maintain a constant output level, where $E_{block} = E_i$ and $I_{block} = I_i$, where $i \in \{1,2\}$. Finally, the remaining case is when both PV panels are shaded. Then, the relays will connect the weak panels in series. In this case, $E_{block} = E_1 + E_2$ and $I_{block} = I_1 = I_2$. The operation of the proposed modular ASB block is summarized in Table 1.

Table 1: Operation of the proposed modular ASB block

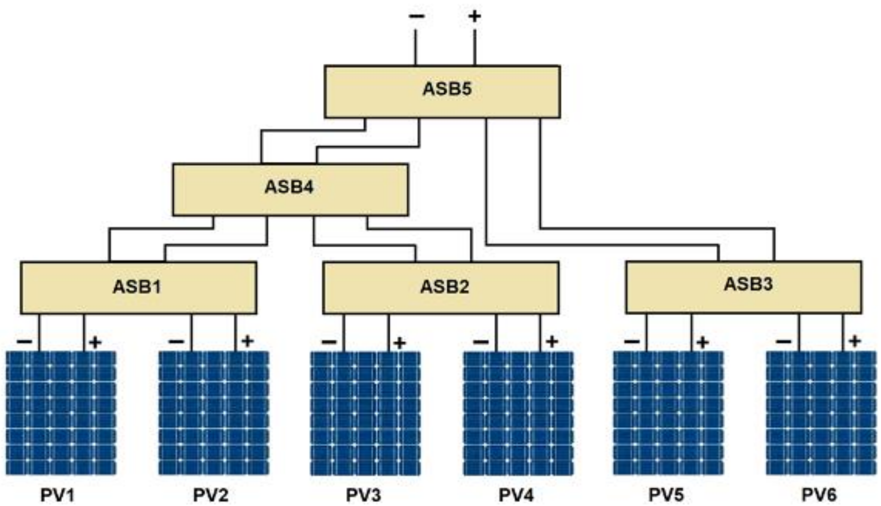
Shading condition		Relay 1	Relay 2	Output Voltage	Connection
PV1	PV2				
Not shaded	Not shaded	NO	NO	E_1//E_2	Parallel
Not shaded	Shaded	NO	NC	E_1	E_1 only
Shaded	Not shaded	NC	NO	E_2	E_2 only
Shaded	Shaded	NC	NC	E_1+E_2	Series

Usually, in printed circuit boards that feature mechanical relays, flyback (or freewheeling) diodes are used, e.g. D1 and D3 in Figure 1. A flyback diode is placed with the reverse polarity of the PV panel output and in parallel to the relay's inductance coil. A flyback diode prevents high voltage spikes from arising when the PV panel is disconnected. That is, when the PV panel is connected to the relay, the voltage of the inductance coil builds up to match that of the power source. The speed at which current can change in an inductor is limited by its time constant. In this case, the time it takes to minimize current flow through the coil is longer than the time it takes for the PV panel to be removed. Upon disconnection, the inductive load in the coil reverses its polarity in an attempt to keep the current flowing. This causes a high voltage potential to build up on the open junctions of the component that controls the relay. This can result in an electrical arc and damage the components controlling the relay. It can also introduce electrical noise that can couple into adjacent signals or power connections and cause microcontrollers to crash 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 about a 0.7 V 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, followed by another ASB to collect the output of the two ASB blocks and produce the final array output. Figure 2 shows 4 and 6-PV panel arrays. For the case of a 6-PV panel array, three ASB blocks are used to connect each one of the three pairs of PV panels. Then, the outputs of two ASB blocks are connected by a fourth ASB to make a 4-PV panel sub-array. Finally, the output of the last pair is connected to the output of the previously connected two pairs by a fifth ASB connection circuit. Generally, an N-PV panel array requires $(N-1)$ ASB connection circuits.



(a) Four-PV panel array



(b) Six-PV panel array

Figure 2: Hierarchical PV arrays.

4. System Analysis and Experimental Results

The proposed ASB-based hierarchical scheme was applied to an eight-PV panel array. The array has been practically implemented using 30W PV panels and seven ASB modules. The specifications of the used PV arrays are given in Table 2.

Table 2: PV panel specifications

Solar Cell Type	Monocrystalline (15.5 x 2.9 cm)			
Pm	Vmp	Imp	Voc	Isc
30W	19.5V	1.6A	22.9V	1.7A

Maximum System Voltage	600 VDC UL
Maximum Series Fuse Rate	5 A
Dimensions	57× 34 ×2.5 cm
Weight	2.8 kg
Cell Efficiency	21.0 %
Standard Test Condition	1000W/m^2, AM 1.5, 25^{o}C
Temperature Coefficient	-23%/^{o}C
Operating Temperature	-40^{o}C to 90^{o}C

Without loss of generality, the eight PV panels are arranged in a single row. However, the PV panels may encounter different shading patterns. As mentioned in Section III, a PV panel is considered as shaded if its output falls below the predefined threshold, i.e., 50% of the maximum output, otherwise, it is considered as not shaded.

Then, there are 28 different possible shading conditions. But, due to the inherent symmetry of the array, the effect of a number of different shading patterns will be the same. For example, the PS condition when a single PV panel is shaded while the other seven panels are not shaded is equivalent to all combinations involving a single PV panel being shaded regardless of the location of the panel. Similarly, there are many equivalent PS patterns for each number of PS panels. Table 3 lists the shading patterns that produce the possible output power values and gives the voltage and current formulas for each case. The practically measured total output voltage, current, and power corresponding to the shading conditions given in Table 3 are recorded in Table 4. Practically, PV panel shading is artificially implemented by covering slightly greater than 50% of its area with a non-transparent cover. Practical tests have shown that this approach causes a drop in the generated voltage and current by approximately the same covering percentage. Considering each one of these shading patterns, the number of different possible distinct power values due to the various shading patterns for the implemented array is 14 values. By ignoring patterns with the same output power, it is concluded that there are six possible distinct power values for the first four PV panels. However, by considering the second four panels, then the number of different possible distinct shading patterns for the implemented array becomes 14 as given in Table 4. As can be observed in the table, different patterns can have the same output power, e.g., patterns 23 and 28, or patterns 30 and 35, etc. In the same table, the theoretical formulas for the total output voltage and current are given for each listed pattern, which are derived according to the operation principle of the designed ASB. In Table 3, I_{ij} represents the average of the currents generated by two series-connected shaded panels with $i \neq j$ and $i, j \in \{1,2,3,4,5,6,7,8\}$. From the results of Table 4, it is observed that the implemented 8-PV array is capable of maintaining a stable level of output voltage, E_o, under all tested PS conditions, with a variation of less than 5% of its maximum. This shows the significance of the proposed ASB-based array and its superiority over controller-based dynamic PV arrays in which more hardware components are required to achieve similar results. Moreover, the generated current is measured by connecting a high power-rated low-resistance load. The total array current, I_o, is the Kirchhoff sum of the currents generated by the active PV panels, which are those still connected panels. As stated in Section III, the ASB connecting a pair of PV panels disconnects the shaded panel if the other panel is not shaded. This prevents shaded panels from imposing electrical loading on their neighbor panels and also prevents fast aging. But, on the other hand, disconnecting these shaded panels causes abrupt variation in the generated current and hence output power.

Generally, the nominal maximum output power that can be gathered from eight 30W PV panels, P_{max}, is 240W. Of course, practically and under PS conditions this value of P_{max} is not achievable; therefore, it is just used as a reference to quantify the performance of the implemented array.

As in Table 4, under the no shading condition, (case 36-shaded), the implemented PV array is capable of generating an output power, P_o, of 222.72W which is about 93% of P_{max}. In this case, all of the PV panels are connected in parallel, but due to the voltage drop across the diodes this loss in voltage occurs and hence the power is reduced. However, P_o drops as the number of shaded panels increases, and even in the case of all panels being shaded (case 29 - shaded), the array is still capable of producing 53.44W, i.e., 85.6% of the total power generated by eight individual shaded PV panels. The practical measurements of E_o, I_o, and P_o of the implemented 8-PV panel array that are obtained under the shading conditions of Table 3 are plotted in Figure 4.

It is worth mentioning that the performance of the implemented array is achieved without the use of a programmable controller and the related hardware such as I/O ports, sensors, and switch matrix. Also, the array can be very easily expanded as described in Section III. Therefore, the proposed scheme can be considered a lower complexity and easier to scale alternative to conventional dynamic reconfigurable PV arrays.

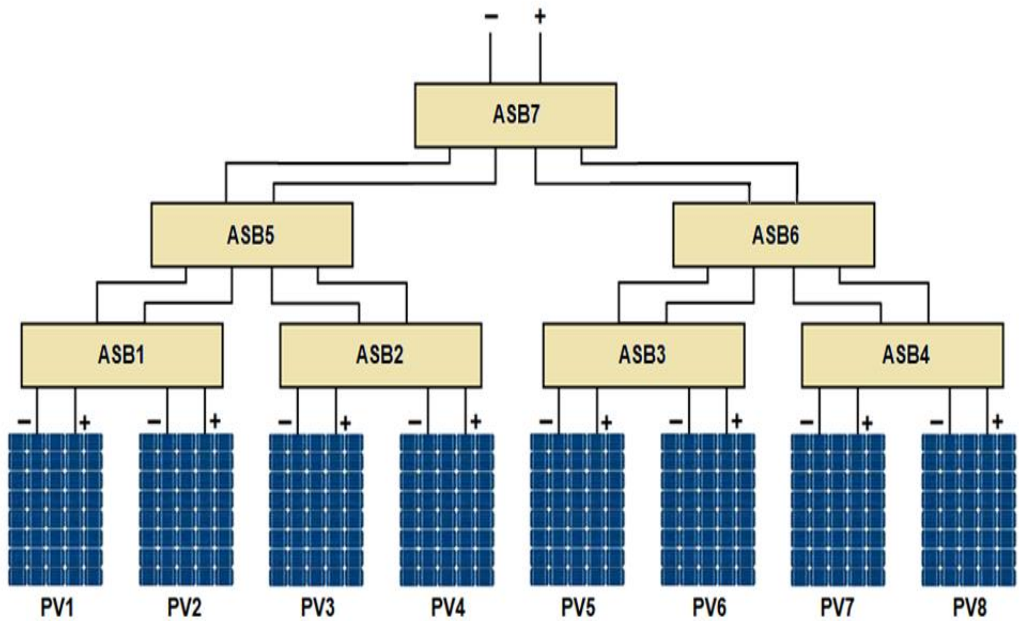


Figure 3: Implemented 8-PV panel array.

Table 3: PS patterns and total output voltage and current formulae of the ASB-based hierarchical 8-PV panel array. Gray-filled cells represent shaded panels

PS case	PV 1	2	3	4	5	6	7	8	Total Output Voltage (E_o)	Total Output Current (I_o)
1	■				■				$E_2//E_3//E_4//E_6//E_7//E_8$	$I_2+I_3+I_4+I_6+I_7+I_8$
2	■	■			■				$(E_1+E_2)//E_3//E_4//E_6//E_7//E_8$	$I_{12}+I_3+I_4+I_6+I_7+I_8$
3	■		■		■				$E_2//E_4//E_6//E_7//E_8$	$I_2+I_4+I_6+I_7+I_8$
4	■	■	■		■				$(E_1+E_2)//E_4//E_6//E_7//E_8$	$I_{12}+I_4+I_6+I_7+I_8$
5	■	■	■	■	■				$(E_1+E_2)//(E_3+E_4)//E_6//E_7//E_8$	$I_{12}+I_{34}+I_6+I_7+I_8$
6					■				$E_1//E_2//E_3//E_4//E_6//E_7//E_8$	$I_1+I_2+I_3+I_4+I_6+I_7+I_8$
7	■				■	■			$E_2//E_3//E_4//E_6//E_7//E_8$	$I_2+I_3+I_4+I_6+I_7+I_8$
8	■	■			■	■			$(E_1+E_2)//E_3//E_4//(E_5+E_6)//E_7//E_8$	$I_{12}+I_3+I_4+I_{56}+I_7+I_8$
9	■		■		■	■			$E_2//E_4//(E_5+E_6)//E_7//E_8$	$I_2+I_4+I_{56}+I_7+I_8$
10	■	■	■		■	■			$(E_1+E_2)//E_4//(E_5+E_6)//E_7//E_8$	$I_{12}+I_4+I_{56}+I_7+I_8$
11	■	■	■	■	■	■			$(E_1+E_2)//(E_3+E_4)//(E_5+E_6)//E_7//E_8$	$I_{12}+I_{34}+I_{56}+I_7+I_8$
12					■	■			$E_1//E_2//E_3//E_4//(E_5+E_6)//E_7//E_8$	$I_1+I_2+I_3+I_4+I_{56}+I_7+I_8$
13	■				■		■		$E_2//E_3//E_4//E_6//E_8$	$I_2+I_3+I_4+I_6+I_8$
14	■	■			■		■		$(E_1+E_2)//E_3//E_4//E_6//E_8$	$I_{12}+I_3+I_4+I_6+I_8$
15	■		■		■		■		$E_2//E_4//E_6//E_8$	$I_2+I_4+I_6+I_8$
16	■	■	■		■		■		$(E_1+E_2)//E_4//E_6//E_8$	$I_{12}+I_4+I_6+I_8$
17	■	■	■	■	■		■		$(E_1+E_2)//(E_3+E_4)//E_6//E_8$	$I_{12}+I_{34}+I_6+I_8$
18					■		■		$E_1//E_2//E_3//E_4//E_6//E_8$	$I_1+I_2+I_3+I_4+I_6+I_8$
19	■				■	■	■		$E_2//E_3//E_4//(E_5+E_6)//E_8$	$I_2+I_3+I_4+I_{56}+I_8$
20	■	■			■	■	■		$(E_1+E_2)//E_3//E_4//(E_5+E_6)//E_8$	$I_{12}+I_3+I_4+I_{56}+I_8$
21	■		■		■	■	■		$E_2//E_4//(E_5+E_6)//E_8$	$I_2+I_4+I_{56}+I_8$

22	■	■	■		■	■	■		$(E_1+E_2)//E_4//(E_5+E_6)//E_8$	$I_{12}+I_4+I_{56}+I_8$
23	■	■	■	■	■	■	■		$(E_1+E_2)//(E_3+E_4)//(E_5+E_6)//E_8$	$I_{12}+I_{34}+I_{56}+I_8$
24					■	■	■		$E_1//E_2//E_3//E_4//(E_5+E_6)//E_8$	$I_1+I_2+I_3+I_4+I_{56}+I_8$
25	■				■	■	■	■	$E_2//E_3//E_4//(E_5+E_6)//(E_7+E_8)$	$I_2+I_3+I_4+I_{56}+I_{78}$
26	■	■			■	■	■	■	$(E_1+E_2)//E_3//E_4//(E_5+E_6)//(E_7+E_8)$	$I_{12}+I_3+I_4+I_{56}+I_{78}$
27	■		■		■	■	■	■	$E_2//E_4//(E_5+E_6)//(E_7+E_8)$	$I_2+I_4+I_{56}+I_{78}$
28	■	■	■		■	■	■	■	$(E_1+E_2)//E_4//(E_5+E_6)//(E_7+E_8)$	$I_{12}+I_4+I_{56}+I_{78}$
29	■	■	■	■	■	■	■	■	$(E_1+E_2)//(E_3+E_4)//(E_5+E_6)//(E_7+E_8)$	$I_{12}+I_{34}+I_{56}+I_{78}$
30					■	■	■	■	$E_1//E_2//E_3//E_4//(E_5+E_6)//(E_7+E_8)$	$I_1+I_2+I_3+I_4+I_{56}+I_{78}$
31	■								$E_2//E_3//E_4//E_5//E_6//E_7//E_8$	$I_2+I_3+I_4+I_5+I_6+I_7+I_8$
32	■	■							$(E_1+E_2)//E_3//E_4//E_5//E_6//E_7//E_8$	$I_{12}+I_3+I_4+I_5+I_6+I_7+I_8$
33	■		■						$E_2//E_4//E_5//E_6//E_7//E_8$	$I_2+I_4+I_5+I_6+I_7+I_8$
34	■	■	■						$(E_1+E_2)//E_4//E_5//E_6//E_7//E_8$	$I_{12}+I_4+I_5+I_6+I_7+I_8$
35	■	■	■	■					$(E_1+E_2)//(E_3+E_4)//E_5//E_6//E_7//E_8$	$I_{12}+I_{34}+I_5+I_6+I_7+I_8$
36									$E_1//E_2//E_3//E_4//E_5//E_6//E_7//E_8$	$I_1+I_2+I_3+I_4+I_5+I_6+I_7+I_8$

Table 4: Output voltage, current and power of the implemented 8-PV array

PS case	*Eo (V)*	*Io (A)*	*Po (W)*	PS case	*Eo (V)*	*Io (A)*	*Po (W)*
1	17.4	9.6	167.04	19	16.7	7.2	120.24
2	16.7	8.8	146.96	20	16.7	6.4	106.88
3	17.4	8	139.2	21	16.7	5.6	93.52
4	16.7	7.2	120.24	22	16.7	4.8	80.16
5	16.7	6.4	106.88	23	16.7	4	66.8
6	17.4	11.2	194.88	24	16.7	8.8	146.96
7	16.7	8.8	146.96	25	16.7	6.4	106.88
8	16.7	8	133.6	26	16.7	5.6	93.52
9	16.7	7.2	120.24	27	16.7	4.8	80.16
10	16.7	6.4	106.88	28	16.7	4	66.8
11	16.7	5.6	93.52	29	16.7	3.2	53.44
12	16.7	10.4	173.68	30	16.7	8	133.6
13	17.4	8	139.2	31	17.4	11.2	194.88
14	16.7	7.2	120.24	32	16.7	10.4	173.68

15	17.4	6.4	111.36	33	17.4	9.6	167.04
16	16.7	5.6	93.52	34	16.7	8.8	146.96
17	16.7	4.8	80.16	35	16.7	8	133.6
18	17.4	9.6	167.04	36	17.4	12.8	222.72

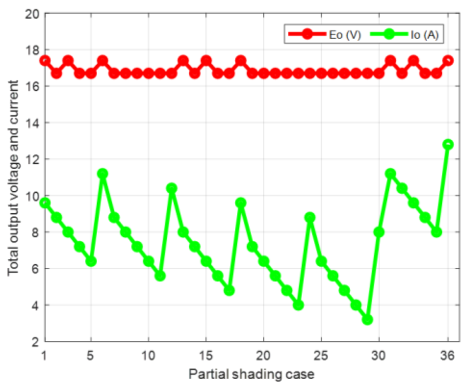


Figure 4: Output of the implemented PV array at each PS condition: Total output voltage and current

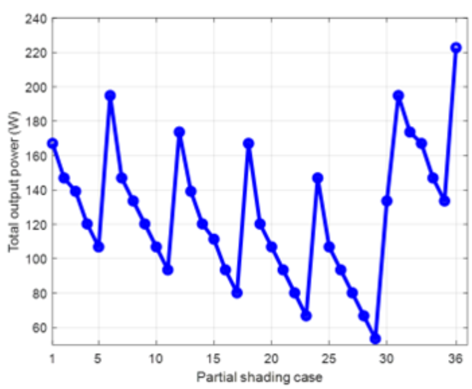


Figure 5: Output of the implemented PV array at each PS condition: Total output power.

5. Conclusion

In this paper, an automatic switching scheme has been proposed to control the dynamic reconfiguration of a PV array subjected 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, different PV array combinations can be constructed. In contrast with conventional dynamic reconfiguration schemes, ASB-based PV arrays do not use programmable controllers and the 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 practical tests of the implemented 8-PV panel array under different PS conditions show the ability of the array to maintain a stable output voltage with a tolerance range of about 5% of its maximum value. 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 activity of the panels. However, the voltage across the flyback and blocking diodes used in the ASB affects the final output voltage and power. A possible future work is to investigate the implementation of the ASB units by using more sophisticated electronic switching approaches. This can lead to faster and more robust performance and also lead to additional features.

References

[1] M. Alkahtani, J. Zhou, Y. Hu, F. Alkasmoul, Z. H. Kiani and C. S. Kuka, "An Experimental Investigation on Output Power Enhancement With Offline Reconfiguration for Non-Uniform Aging Photovoltaic Array to Maximise Economic Benefit," in IEEE Access, vol. 9, pp. 87510-87519, 2021.

[2] Hegazy Rezk, Ahmed Fathy, Mokhtar Aly, "A robust photovoltaic array reconfiguration strategy based on coyote optimization algorithm for enhancing the extracted power under partial shadow condition, Energy Reports," Volume 7,2021, Pages 109-124.

[3] Alkahtani, M.; Wu, Z.; Kuka, C.S.; Alahammad, M.S.; Ni, K. A Novel PV Array Reconfiguration Algorithm Approach to Optimising Power Generation across Non-Uniformly Aged PV Arrays by Merely Repositioning. J 2020, 3, 32-53.

[4] Srinivasan, A., Devakirubakaran, S., Sundaram, B. M., Balachandran, P. K., Cherukuri, S. K., Winston, D. P., ... & Alhelou, H. H. (2021). L-shape propagated array configuration with dynamic

reconfiguration algorithm for enhancing energy conversion rate of partial shaded photovoltaic systems. IEEE Access, 9, 97661-97674.

[5] J. Zhang, Q. Zhou, J. Li, L. Zhao, D. Wang and L. Liu, "Overview the Approaches for Maximum Power Point of Photovoltaic Arrays in partially Shaded Environment," 2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2), 2020, pp. 2568-2571.

[6] Pachauri, R. K., Mahela, O. P., Sharma, A., Bai, J., Chauhan, Y. K., Khan, B., & Alhelou, H. H. (2020). Impact of partial shading on various PV array configurations and different modeling approaches: A comprehensive review. IEEE Access, 8, 181375-181403.

[7] M. Palpandian, D. P. Winston, B. P. Kumar, C. S. Kumar, T. S. Babu and H. H. Alhelou, "A New Ken-Ken Puzzle Pattern Based Reconfiguration Technique for Maximum Power Extraction in Partial Shaded Solar PV Array," in IEEE Access, vol. 9, pp. 65824-65837, 2021.

[8] C. V. Chandrakant and S. Mikkili, "A typical review on static reconfiguration strategies in photovoltaic array under non-uniform shading conditions," in CSEE Journal of Power and Energy Systems, 2020.

[9] Nazer, M. N. R., Noorwali, A., Tajuddin, M. F. N., Khan, M. Z., Tazally, M. A. I. A., Ahmed, J., ... & Kumar, N. M. (2021). Scenario-based investigation on the effect of partial shading condition patterns for different static solar photovoltaic array configurations. IEEE Access, 9, 116050-116072.

[10] Belhachat F, Larbes C. , “Modeling, analysis and comparison of solar photovoltaic array configurations under partial shading conditions”, Sol Energy 120: 399–418, 2015.

[11] Belhaouas N, Cheikh MSA, Agathoklis P, “Pv array power output maximization under partial shading using new shifted pv array arrangements”, Appl Energ 187: 326–337, 2017.

[12] Antonino Laudani, Gabriele MariaLozito, Valentina Lucaferri, Martina Radicioni and Francesco Riganti Fulginei, “Circuital topologies and reconfiguration strategies for PV systemsin partial shading conditions: A review”, AIMS Energy, 6(5): 735–763.

[13] M. Azzouzi, D. Popescu, and M. Bouchahdane, “Modeling of Electrical Characteristics of Photovoltaic Cell Considering Single-Diode Model”, Journal of Clean Energy Technologies, Vol. 4, No. 6, November 2016

[14] Tabanjat, A., Becherif, M., & Hissel, D. (2015), “Reconfiguration solution for shaded PV panels using switching control,” Renewable Energy, 82, 4–13.

[15] Hariharan, R., Chakkarapani, M., Saravana Ilango, G., & Nagamani, C. (2016), “A Method to Detect Photovoltaic Array Faults and Partial Shading in PV Systems”, IEEE Journal of Photovoltaics, 6(5), 1278–1285.

[16] Orozco-Gutierrez, M. L., Spagnuolo, G., Ramirez-Scarpetta, J. M., Petrone, G., & Ramos-Paja, C. A. (2016), “Optimized Configuration of Mismatched Photovoltaic Arrays”, IEEE Journal of Photovoltaics, 6(5), 1210–1220.

[17] Deshkar, S. N., Dhale, S. B., Mukherjee, J. S., Babu, T. S., & Rajasekar, N. (2015), “Solar PV array reconfiguration under partial shading conditions for maximum power extraction using genetic algorithm”, Renewable and Sustainable Energy Reviews, 43, 102–110.

[18] Sanseverino, E. R., Ngoc, T. N., Cardinale, M., Li Vigni, V., Musso, D., Romano, P., & Viola, F. (2015), “Dynamic programming and Munkres algorithm for optimal photovoltaic arrays reconfiguration”, Solar Energy, 122, 347–358

[19] Abdelghani Harrag, Sabir Messalti,(2016) “Adaptive GA-based reconfiguration of photovoltaic array combating partial shading conditions”, The Natural Computing Applications Forum 2016 springer

[20] B. Praveen Kumar, D. Prince Winston, S. Cynthia Christabel, and S. Venkatanarayanan, “Implementation of a Switched PV Technique for Rooftop 2 kW Solar PV to Enhance Power during Unavoidable Partial Shading Conditions” , Journal of Power Electronics, Vol. 17, No. 6, pp. 1600-1610, November 2017,

[21] Rajan, N. A., Shrikant, K. D., Dhanalakshmi, B., & Rajasekar, N. (2017), “Solar PV array reconfiguration using the concept of Standard deviation and Genetic Algorithm”, Energy Procedia, 117, 1062–1069.

[22] Pareek, S., Chaturvedi, N., & Dahiya, R. (2017), "Optimal interconnections to address partial shading losses in solar photovoltaic arrays", Solar Energy, 155, 537–551.

[23] Iraji, F., Farjah, E., & Ghanbari, T. (2018), "Optimisation method to find the best switch set topology for reconfiguration of photovoltaic panels", IET Renewable Power Generation, 12(3), 374–379.

[24] Fathy, A. (2018), "Recent meta-heuristic grasshopper optimization algorithm for optimal reconfiguration of partially shaded PV array", Solar Energy, 171, 638–651.

[25] Tazehkand, M. Z., Fathi, S. H., Eskandari, A., & Milimonfared, J. (2018, February). Optimal reconfiguration of PV modules in an array without any constraint on structure by the use of genetic algorithm. In 2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC) (pp. 145-150).

[26] Narayanaswamy, V. S., Ayyanar, R., Spanias, A., Tepedelenlioglu, C., & Srinivasan, D. (2019), "Connection Topology Optimization in Photovoltaic Arrays using Neural Networks", 2019 IEEE International Conference on Industrial Cyber Physical Systems (ICPS).

[27] Kareem, Parween Raheem. "Performance of PV panel under shaded condition." NTU Journal of Renewable Energy 1.1 (2021).

[28] Sharif, M. A. (2021). Numerical Simulation of a Ground-Supported Solar Panel PV Array Subjected to Periodic Flow. NTU Journal of Renewable Energy, 1(1), 50-55.

[29] Ali, Z., Abdullah, Z. M., Naser, B. A., Daoud, R. W., & Ahmed, A. H. (2021). Design of a Single-Phase Inverter for Solar Energy Conversion System. NTU Journal of Renewable Energy, 1(1), 38-42.

[30] Bularka, S., & Gontean, A. (2017), "Dynayamic PV array reconfiguration under suboptimal conditions in hybrid solar energy harvesting systems", IEEE 23rd International Symposium for Design and Technology in Electronic Packaging (SIITME).

[31] Mohamad Hossien Nahidan, Mehdi Niroomand, and Behzad Mirzaeian Dehkordi, "Power Enhancement under Partial Shading Condition Using a Two-Step Optimal PV Array Reconfiguration", International Journal of Photoenergy, Volume 2021, 2021.

[32] Schettino, G.; Pellitteri, F.; Ala, G.; Miceli, R.; Romano, P.; Viola, F., "Dynamic Reconfiguration Systems for PV Plant: Technical and Economic Analysis", Energies, Volume 13, No. 8, 2020.

[33] Matam, M., & Barry, V. R. (2018), "Improved performance of Dynamic Photovoltaic Array under repeating shade conditions", Energy Conversion and Management, 168, 639–650.