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Dynamic Reconfiguration Scheme of PV Arrays to Achieve Stable Output Voltage under Partial Shading Conditions

Omar Shakir Hamad[1], Mohammed Ghadhban Ahmed[2], Sabah Khudhair Ali[3], Abdulrahman Ikram Siddiq[4]
[1,2,3,4]Department of Electronics and Control Engineering, Northern Technical University, Kirkuk, Iraq.

ABSTRACT: Photovoltaic (PV) arrays are widely recognized as a significant source of clean and renewable electricity. However, they are susceptible to unavoidable non-uniform partial shading (PS) caused by factors such as clouds, buildings, and dust. PS leads to issues like hot spots, mismatch losses, and degradation of output power. Dynamic reconfiguration is a commonly used method to mitigate the effects of PS, where the interconnection of PV panels is modified based on shading conditions to maximize output. Dynamic reconfiguration techniques typically involve the use of sensors, programmable controllers, and switch matrices to achieve optimal operation. However, these approaches often suffer from system complexity and scalability limitations. To address these challenges, this paper proposes an automatic dynamic reconfiguration scheme that leverages the irradiation activity of PV panels to control their interconnection. A modular building block is introduced. These building blocks enable hierarchical interconnection of PV arrays, eliminating the need for a programmable microcontroller and associated circuitry, thus reducing complexity and cost. Furthermore, the hierarchical design facilitates easy scaling and expansion of the system. The effectiveness of the proposed reconfiguration scheme has been verified through both simulation and analytic results.

KEYWORDS: Dynamic Reconfiguration, PV Arrays, Partial Shading, Stable Output Voltage, Renewable Energy Systems.

I. INTRODUCTION

Rising environmental concerns, increasing energy demand driven by technological advancements, and a growing global population are increasingly highlighting the need for eco-friendly and efficient energy sources. Photovoltaic (PV) solar energy generation has emerged as a promising renewable energy solution [1]. However, the efficiency of PV solar systems can be affected by various factors, including partial shading (PS) [2]. PS occurs when external objects such as buildings, trees, clouds, or dust obstruct the sunlight reaching the PV panels, resulting in reduced power generation for the entire system [1, 2]. Moreover, PS can lead to the formation of hot spots in shaded areas, potentially damaging PV modules [2, 3].

To mitigate the effects of PS, several measures and techniques have been proposed. One approach involves the use of bypass diodes connected across PV modules to prevent hot spot formation, but this can shift the voltage-current relationship of the module away from the maximum power point [4-7]. Another technique involves different interconnection configurations of PV modules to form solar arrays, with total cross-tied (TCT) configurations showing higher tolerance to PS [6].

Reconfiguration of PV modules within an array is another effective technique to mitigate the effects of PS. Reconfiguration methods can be categorized into static and dynamic techniques. Static reconfiguration involves altering the physical arrangement of modules in the array to distribute the shading effects, while dynamic reconfiguration aims to optimize power production by dynamically changing the interconnections based on the irradiance condition [5, 6, 8]. Dynamic reconfiguration typically requires monitoring the system with sensors and utilizing algorithms, such as optimization techniques, artificial neural networks, genetic algorithms, or fuzzy logic, to determine the optimal configuration [5, 6, 8].

Hybrid methods combining different reconfiguration algorithms have also been explored and shown to improve system performance in terms of output power, reconfiguration speed, and PV panel lifetime [18, 33]. However, these systems tend to be more complex due to the implementation of hybrid algorithms.

While dynamic reconfiguration offers potential benefits, the complexity of systems employing programmable controllers and a large number of switches should be considered [4, 31-33]. Previous research has proposed reconfiguration techniques using sensors and switches, demonstrating the ability to mitigate a significant portion of shading effects. However, fewer switches result in less flexibility to handle PS. Therefore, this paper proposes a switching technique that maintains sufficient reconfiguration flexibility while reducing system complexity by eliminating the need for a programmable controller. The proposed technique relies on automatic switching based directly on the activity of PV panels. Experimental tests show that the switch count of the proposed switching network is significantly lower compared to conventional semiconductor switching networks.

Scalability is another consideration in PV array reconfiguration. Dynamic reconfiguration methods face challenges in scaling up the system size [8, 9]. Adding or removing PV modules requires extensive modifications to the control system hardware and heuristic reconfiguration algorithms. This limitation restricts dynamic reconfiguration to small-scale installations [10, 11]. Additionally, despite the use of microcontrollers and programmed reconfiguration algorithms, no heuristic algorithm has been found to be universally successful in producing optimal solutions under all possible partial shading conditions [12, 13].

To address these challenges, this paper proposes an automatic dynamic PV array reconfiguration technique that does not rely on microcontrollers or software reconfiguration algorithms. The technique enables automatic and flexible parallel-series reconfiguration of PV modules based on their activity. To facilitate scalability, a hierarchical structure is introduced, allowing for modular reconfiguration of two PV panels.

The remainder of the paper is organized as follows: Section II provides a review of related works, Section III describes the proposed automatic reconfiguration scheme, Section IV presents the analysis and experimental implementation of the scheme, and finally, Section V concludes the paper.

II. LITERATURE REVIEW

Dynamic reconfiguration of PV modules in response to partial shading is typically achieved using programmed microcontrollers for control. The microcontroller receives power generation data from each PV panel and analyzes the shading pattern. Based on a reconfiguration algorithm, the microcontroller adjusts the electrical structure of the PV array using a switching matrix with different objectives, such as maximizing output power and maintaining a constant load voltage. Previous studies have extensively explored the impact of heuristic reconfiguration algorithms on system performance, utilizing various optimization techniques such as mathematical calculations, artificial neural networks, genetic algorithms, and fuzzy logic.

Hybrid methods that combine multiple reconfiguration algorithms have been investigated to enhance system performance in terms of output power, reconfiguration speed, and PV panel lifetime. Although hybrid algorithms offer advantages, they tend to introduce complexity to the system compared to individual reconfiguration algorithms. Furthermore, while some studies have considered specific partial shading conditions, the ability of the reconfiguration algorithm to handle various shading scenarios remains a challenge. Certain controllers may struggle to differentiate between different shading conditions, leading to performance degradation.

The economic benefits of dynamic PV array reconfiguration under partial shading conditions have also been examined. For instance, repositioning aged PV modules can improve power production and eliminate the need for costly replacements. However, dynamic reconfiguration typically requires a programmable controller and a significant number of switches. Attempts have been made to disperse shading effects using sensor and switch configurations, and alternative schemes have proposed the use of double pole double throw switches. It is generally observed that reducing the number of switches limits the system's flexibility in mitigating the effects of partial shading.

To address these challenges, this paper proposes a reconfiguration technique that maintains reconfiguration flexibility while reducing system complexity. The approach involves discarding the use of a programmable controller and replacing it with an automatic switching technique directly controlled by PV panel activity. Experimental tests demonstrate that the proposed switching network requires one-third the number of switches compared to conventional semiconductor switching networks. This reduction in switch count significantly decreases overall system complexity, as the controller no longer needs to perform exhaustive calculations for each shading condition to determine suitable switching.

III. PROPOSED RECONFIGURATION SCHEME

In this paper, an automatic dynamic reconfiguration scheme is proposed to address the challenges of partial shading in PV arrays. The scheme eliminates the need for a traditional programmable microcontroller by directly updating the interconnection of PV modules based on their activity in response to shading conditions. To ensure scalability, a hierarchical structure is employed, and a modular building block called (3-PV Controller). In order to evaluate the performance of the proposed system, the 3-PV Controller is simulated in Matlab. First of all, the adopted PV panel is the 98W Aplus Energy AP-PVROOF-319 monocrystalline panel whose specifications are given in Table-1. Its performance has been evaluated by simulation under different irradiance values as shown in Fig.1 and Table-2.

Table-1 Aplus Energy AP-PVROOF-319

Maximum Power (W)	98.332
Cells per module (NPanel)	24
Open circuit voltage Voc (V)	15.2
Short-circuit current Isc (A)	8.61
Voltage at MPP Vmp (V)	12.4
Current at MPP Imp (A)	7.93
Current at MPP Imp (A)	7.93

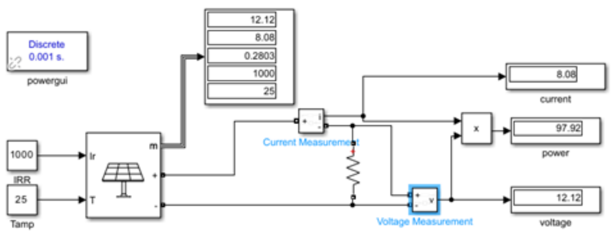

Fig.1 Simulation of a single solar panel

In a PV array, under normal conditions (no shading), the PV panels are expected to generate equal output voltages. When shading occurs, the output voltage of a PV panel falls below a predefined threshold, such as 50% of its maximum output. The proposed 3-PV Controller scheme, shown in Fig. 2, enables efficient connection adaptation to shading conditions, resulting in enhanced output voltage stability of the PV array.

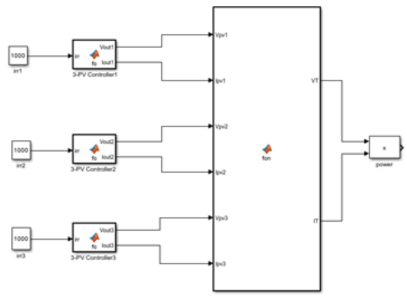

Fig.2 The 3-PV Controller

Table-2 The results of simulating a signal solar Panel with constant load resistance 1.5 Ω

IRR	Vm(v)	Im(A)	Pm(w)
0	0	0	0
50	0.6462	0.4303	0.27806
100	1.29	0.8602	1.10966
150	1.932	1.288	2.48842
200	2.575	1.715	4.41613
250	3.21	2.14	6.8694
300	3.845	2.563	9.85474
350	4.479	2.986	13.3743
400	5.11	3.407	17.4098
450	5.739	3.826	21.9574
500	6.366	4.244	27.0173
550	6.991	4.661	32.5851
600	7.614	5.076	38.6487
650	8.235	5.49	45.2102
700	8.853	5.902	52.2504
750	9.467	6.311	59.7462
800	10.07	6.716	67.6301
850	10.66	7.11	75.7926
900	11.22	7.481	83.9368
950	11.71	7.81	91.4551
1000	12.12	8.08	97.9296

The analysis of this system is divided into two parts. The first part focuses on scenarios where the panel voltage remains constant and a weak PV panel is neglected. When the incident radiation on the solar panel is less than 200W/m^2, then this condition is referred to as "low radiation" throughout the analysis.

As shown in Table 3, when the solar irradiance falls on the panels with no shading, the panels work at their maximum output. When the panels are placed in shadow cases, they are considered to operate at 50% of their maximum values. The mathematical formulas of the output voltage and current under different shading conditions are given in Table-3. In Table-4 the numerical values of the voltage and current results are given. Similar cases in terms of the number of shaded panels are found in Table 3, namely, the shade cases of 2, 3 and 5 when solar radiation falls on a single panel and the remaining two panels are shaded. In this case, the proposed system connects the shaded panels in series, while the panel receiving full radiation is connected in parallel with them. The second similarity is in shadow cases 4, 6 and 7 when solar radiation falls on two panels and the remaining single panel is under shading. The system connects the unshaded panels in parallel while neglecting the shaded panel. The third case is when all of the three solar panels are shaded. In this case, one solar panel is neglected, and the other solar panels are connected in series to maintain the required output voltage. Finally, when the three solar panels are unshaded and receiving full solar radiation, in this case, they would be connected all parallel.

In order to utilize all of the power generated by the panels, the second part of system analysis is made with the weak PV panel is considered without neglecting it, as has been done in cases 1, 4, 6 and 7 in Table 3. For this analysis, the connection and output voltage and current formulas with the numerical values are given in Table-5 and Table-6, respectively. From Table 5, there is a similarity in mathematical formulas with Table-3 in 2, 3, 5 and 8. Different formulas are used for the cases 1, 4, 6 and 7, because the weak panel is not ignored. In a scenario when solar radiation falls on two solar panels and one panel is shaded, the connection strategy will be parallel to the two panels that receive radiation and the shaded panel is connected in a series with them. Also, when all of the panels are under shading, in this case all of the weak panels are connected in series.

Table-3 Output voltage and current formulas when weak panel is neglected

Shading	PV1	PV2	PV3	Total Output Voltage (VT)	Total Output Current (IT)
1	0	0	0	VPV1+VPV2	(IPV1+IPV2)/2
2	0	0	1	((VPV1+VPV2)+VPV3)/2	(IPV1+IPV2)+IPV3
3	0	1	0	((VPV1+VPV3)+VPV2)/2	((IPV1+IPV3)/2)+IPV2
4	0	1	1	(VPV2+VPV3)/2	IPV2+IPV3
5	1	0	0	(VPV1+(VPV2+VPV3))/2	IPV1+(IPV2+IPV3)
6	1	0	1	(VPV1+VPV3)/2	IPV1+IPV3
7	1	1	0	(VPV1+VPV2)/2	IPV1+IPV2
8	1	1	1	(VPV1+VPV2+VPV3)/3	IPV1+IPV2+IPV3

Table-4 Output voltage and current values when weak panel is neglected

Shading	PV1	PV2	PV3	VOUT	IOUT	POUT
1	0	0	0	11.48	3.83	43.92
2	0	0	1	11.8	11.91	140.54
3	0	1	0	11.8	11.91	140.54
4	0	1	1	12.12	16.16	195.86
5	1	0	0	11.8	11.91	140.54
6	1	0	1	12.12	16.16	195.86
7	1	1	0	12.12	16.16	195.86
8	1	1	1	12.12	24.24	293.79

Table-5 Output voltage and current formulas when weak panel is not neglected

Shading	PV1	PV2	PV3	Total Output Voltage (VT)	Total Output Current (IT)
1	0	0	0	Vpv1+Vpv2+Vpv3	(Ipv1+Ipv2+Ipv3)/3
2	0	0	1	((Vpv1+Vpv2)+Vpv3)/2	((Ipv1+Ipv2)/2)+Ipv3
3	0	1	0	((Vpv1+Vpv3)+Vpv2)/2	(((Ipv1+Ipv3)/2)+Ipv2)
4	0	1	1	(Vpv1+((Vpv2+Vpv3)/2))	(Ipv1+(Ipv2+Ipv3))/2
5	1	0	0	(Vpv1+(Vpv2+Vpv3))/2	(Ipv1+(Ipv2+Ipv3)/2)
6	1	0	1	(((Vpv1+Vpv3)/2)+Vpv2)	((Ipv1+Ipv3)+Ipv2)/2
7	1	1	0	(Vpv1+Vpv2)/2+Vpv3	((Ipv1+Ipv2)+Ipv3)/2
8	1	1	1	(Vpv1+Vpv2+Vpv3)/3	(Ipv1+Ipv2+Ipv3)

Table-6 Output voltage and current values when weak panel is not neglected

Shading	PV1	PV2	PV3	VOUT	IOUT	POUT
1	0	0	0	17.22	3.82	65.88
2	0	0	1	11.8	11.91	140.53
3	0	1	0	11.8	11.91	140.53
4	0	1	1	17.86	9.99	178.47
5	1	0	0	11.8	11.91	140.53
6	1	0	1	17.86	9.99	178.47
7	1	1	0	17.86	9.99	178.47
8	1	1	1	12.12	24.24	293.78

Next, a 3x3 PV array is constructed by using the designed 3-PV Controller, as shown in Fig.3.

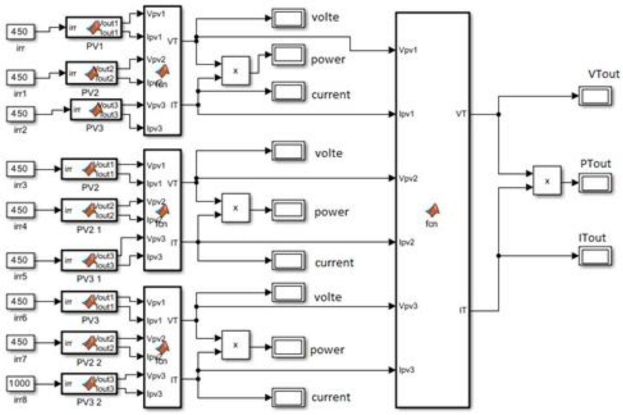

Fig.3 The 3x3 PV array

In this research, the fifteen partial shadowing conditions were used to evaluate the system performance in terms of array output voltage, current and power, as shown in Tables (7, 8 and 9). The PV panels are arranged in a 3x3 matrix as shown in Fig.4.

PV1	PV2	PV3
PV4	PV5	PV6
PV7	PV8	PV9

Fig.4 PV panel arrangement

By studying the first system, it shows the stability of voltages with the neglecting of the shadowed board and its work as previously studied. In the second system (without neglecting the shadowed panel), specific considerations were taken into account. There are cases where the results are consistent with the without neglecting weak panels system (Neglecting the weak panel) according to Table- 7 and 8. However, the varying cases in the results were simulated by considering whether the solar panels were in shade, meaning maximizing the utilization of solar panels. In the following example, the first shadow case is shown in Fig. 5, where the first column of the array is under shading while the rest are receiving full irradiance.

PV1	PV2	PV3
PV4	PV5	PV6
PV7	PV8	PV9

Fig.5 Shadow Case 1

The first system (Neglecting the weak panel) has been studied according to Table 7. The first case of shadow is read with a current value of 48.84 A, a voltage of 12.12 V, and a power of 591.9408 W. In the second system, without neglecting weak panels according to Table 8, the first case of shadow was read with a current value of 29.98 A, a voltage of 17.86 V and a power of 535.443 W. In the last system TCT as per Table -9, the first case of shadow is read with a current value of 19.99 A, a voltage of 29.98 V and a power of 599.3002 W.

Table-7 Nine-PV array with neglecting weak panels

Shading	PV1	PV2	PV3	PV4	PV5	PV6	PV7	PV8	PV9	VOUT (V)	IOUT (A)	POUT (W)
1	0	1	1	0	1	1	0	1	1	12.12	48.84	591.94
2	0	0	0	0	0	0	0	0	0	11.48	11.48	131.79
3	0	0	1	0	0	1	0	0	1	11.8	35.72	421.4
4	0	0	0	1	1	1	1	1	1	11.91	52.31	623.01
5	0	0	0	0	0	0	1	1	1	11.69	31.89	372.79
6	0	1	1	1	1	1	1	1	1	12.12	64.64	783.43
7	0	0	1	0	1	1	1	1	1	12.01	52.31	628.24
8	0	0	0	0	0	1	0	1	1	11.8	31.89	376.30
9	0	0	0	0	0	0	0	0	1	11.58	19.56	226.50
10	1	0	0	0	1	0	0	0	1	11.8	35.72	421.49
11	0	0	0	1	1	0	0	0	0	11.69	23.81	278.33
12	0	0	0	0	1	0	0	1	1	11.91	36.15	430.54
13	0	0	1	1	1	1	1	1	1	12.01	60.39	725.28
14	0	0	1	0	0	1	1	1	1	11.91	48.05	572.27
15	0	1	0	0	1	0	0	1	0	11.8	35.72	421.49

These nine panels were simulated using Matlab software, as shown above in Fig.3. Through this simulation, the highest power output in the system Neglecting the weak panel was achieved, with a value of (783.4 W) as indicated in the Table-7. In another system Without neglecting the weak panel configuration, the highest power output was obtained with a value of (820.6 W) as indicated in the Table-8. It was observed from the results that using the nine panels yielded better results compared to using only three panels, thus demonstrating an improvement in power capacity.

Table-8 Nine-PV array without neglecting weak panels

Shading	PV1	PV2	PV3	PV4	PV5	PV6	PV7	PV8	PV9	VOUT (V)	IOUT (A)	POUT (W)
1	0	1	1	0	1	1	0	1	1	29.98	19.99	599.30
2	0	0	0	0	0	0	0	0	0	17.22	11.48	197.68
3	0	0	1	0	0	1	0	0	1	23.6	15.73	371.22
4	0	0	0	1	1	1	1	1	1	29.98	19.99	599.30
5	0	0	0	0	0	0	1	1	1	23.6	15.73	371.22
6	0	1	1	1	1	1	1	1	1	34.23	22.82	781.12
7	0	0	1	0	1	1	1	1	1	29.98	19.99	599.30
8	0	0	0	0	0	1	0	1	1	23.6	15.73	371.22
9	0	0	0	0	0	0	0	0	1	19.34	12.9	249.48
10	1	0	0	0	1	0	0	0	1	25.73	17.15	441.26
11	0	0	0	1	1	0	0	0	0	21.47	14.31	307.23
12	0	0	0	0	1	0	0	1	1	25.73	17.15	441.26
13	0	0	1	1	1	1	1	1	1	32.11	21.4	687.15
14	0	0	1	0	0	1	1	1	1	27.85	18.57	517.17
15	0	1	0	0	1	0	0	1	0	23.6	15.73	371.22

Table- Nine-PV array TCT configuration

Shading	PV1	PV2	PV3	PV4	PV5	PV6	PV7	PV8	PV9	VOUT (V)	IOUT (A)	POUT (W)
1	0	1	1	0	1	1	0	1	1	17.86	29.98	535.44
2	0	0	0	0	0	0	0	0	0	17.23	11.48	197.8
3	0	0	1	0	0	1	0	0	1	11.8	35.72	421.49
4	0	0	0	1	1	1	1	1	1	13.82	52.31	722.92
5	0	0	0	0	0	0	1	1	1	15.58	31.89	496.84
6	0	1	1	1	1	1	1	1	1	14.03	58.47	820.33
7	0	0	1	0	1	1	1	1	1	13.93	46.14	642.73
8	0	0	0	0	0	1	0	1	1	15.62	25.73	401.90
9	0	0	0	0	0	0	0	0	1	15.41	19.56	301.42
10	1	0	0	0	1	0	0	0	1	11.8	35.72	421.49
11	0	0	0	1	1	0	0	0	0	17.43	17.64	307.46
12	0	0	0	0	1	0	0	1	1	15.62	25.73	401.90
13	0	0	1	1	1	1	1	1	1	12.01	60.39	725.28
14	0	0	1	0	0	1	1	1	1	11.91	48.05	572.27
15	0	1	0	0	1	0	0	1	0	11.8	35.72	421.49

It worth mentioning that the same proposed building block, 3-PV Controller, can be easily used to construct larger PV arrays without the need to redesign the controller. Fig. 6 shows how the 9x9 array can be scaled up to 18-PV panel array.

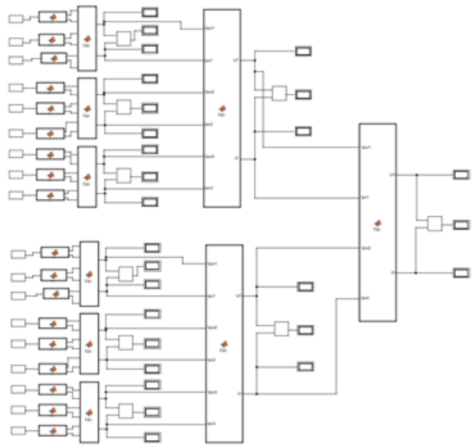

Fig. 6 Expanded 18-PV panel array

IV. RESULTS AND DISCUSSION

However, in the remaining cases, there was variation in the results due to the following reasons. As indicated in Table- 7, in the first system (Neglecting the weak panel), the voltage is maintained almost constant and varies from 11.8 to 12.12 volts, while the power ranges from about 131.8 to 783.4 Watts depending on the connection of the solar panels.

In the second system (without neglecting the weak panel), the voltage is adjusted and varies from 11.8 to 17.86 Volts, as indicated in Table 8, as is the generated power, which ranges from 197.8 to 820.3 Watts depending on the selected solar panel.

In the final system TCT, the voltage is changed from 17.22 to 34.23 Volts, as shown in Table- 9, as well as the power generated, ranging from about 197.7 to 781.1 Watts depending on the selected solar panels. In the TCT system, the solar panels are interconnected in a fully cross-tied manner, meaning that the top and bottom wires intersect at connection points. As a result, the solar panels in the TCT system are connected in a way that enhances system efficiency and reduces energy loss [2, 4]. By using the TCT system, a uniform current distribution is achieved among the solar panels, which improves the system's performance and maximizes its utilization of available solar energy. This type of system can be beneficial in cases where there is partial shading on the solar panels or variations in illumination levels across the solar panel area.

For the TCT system, a relatively larger variation in output voltage is observed as compared with the results of the proposed systems. This is due to the parallel and series connection of the system TCT, which leads to instability and variation in the results. If compared with the first and second systems, it can be observed that the output power of these proposed systems is higher than that of the TCT system. Therefore, it can be concluded that the proposed systems are better in terms of output power, output voltage stability and in solar panel utilization, as shown in Figs. 7 and 8.

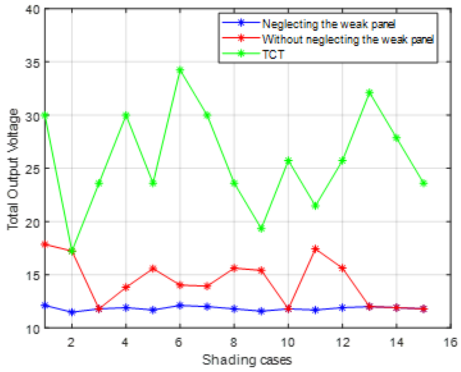

Fig.7 Total Output Voltage System 15 PV Shading cases

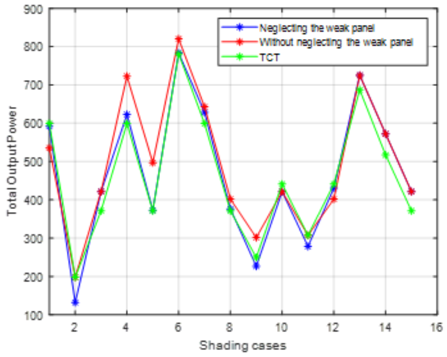

Fig.8 Total Output Power System 15 PV Shading cases

V. CONCLUSION

This paper presents an innovative automatic dynamic reconfiguration scheme designed to address the challenges posed by partial shading in PV arrays. The proposed scheme eliminates the dependency on a traditional programmable microcontroller and improves the stability of the generated voltage level; by dynamically adjusting the interconnection of PV modules based on their response to shading conditions. The system incorporates a hierarchical structure and a modular building block referred to as the 3-PV Controller, ensuring scalability and adaptability.

Through extensive simulations conducted in Matlab, the performance of the proposed 3-PV Controller was evaluated under various irradiance conditions. A 9x9 PV array has been studied. The study considered two scenarios of operation for the proposed system, namely by neglecting the weak panel and without neglecting weak panel. The simulation results were also compared with a conventional TCT system. The results showed significant variation in performance among these systems.

The first system, which neglects the weak panel, has achieved an output voltage range of 11.8 to 12.12 Volts and power ranging from 131.8 to 783.4 Watts. In the second system, which did not neglect the weak panel, a slight expansion in the output voltage range is observed (from 11.8 to 17.86 Volts), but it was capable to harvest higher output power from 197.8 to 820.334 Watts. The TCT system, with voltage ranging from 17.22 to 34.23 Volts, showed power output between 197.7 and 781.1 Watts. Therefore, it can be concluded that the proposed systems have superior performance in terms of output voltage stability and a comparable performance in terms of the generated power.

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