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A New Static PV Array Reconfiguration for Increasing Maximum Power, Case Study: Al-Nahrain University

Anas Lateef Mahmood
Department of Electronic and Communications Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq

Correspondance
*Anas Lateef Mahmood
Department of Electronic and Communications Engineering, College of Engineering,
Al-Nahrain University, Baghdad, Iraq
Email: anas.lateef.1@nahrainuniv.edu.iq

Abstract
Enhancing the generated power. Different conventional reconfiguration techniques can be used for this purpose like total-cross-tied (TCT), bridge-linked (BL), and series-parallel (SP) ... etc. This article propose a new static reconfiguration technique named Row Odd Even reconfiguration (ROE) to increase the maximum power generated from PV array with the effect of partial shading condition. The proposed reconfiguration has been tested on a 3×22 PV array suggested to provide power to the department of electronic and communications engineering at Al-Nahrain University, Baghdad, Iraq. The results of the proposed reconfiguration are compared with the (SP, TCT, and Zig-zag) in terms of mismatch power losses (MPL), fill factor (FF), and efficiency (η) at the maximum generated power of PV array. In all cases, the performance of the new reconfiguration gave the best performance when compared with (SP, TCT, and Zig-zag). The new reconfiguration achieved an improvement in the maximum power point (MPP) and efficiency about 33%, 28% and 7% when compared with the (SP), (TCT) and (Zig-zag) reconfigurations respectively.

Keywords
PV Array, Static Reconfiguration Techniques, Partial Shading Condition, Maximum Generated Power.

I. Introduction

Conventional, nonrenewable sources is still represents the majority of world's energy consumption, which have share in hazardous emissions, hence will increased global warming in addition to other severe effects on the weather and environmental conditions [1–3]. Oil prices increases, fossil fuel reservoirs depletion, energy security issues, and the global warming have been the most important stimulus behind the increasing attention for using renewable energy sources in power generation [4]. Among the renewable sources available, solar energy has received the significant attention. Alternative and clean energy is produced by solar energy which has a density of around (1 kW/m^2) received from the sun at sea level.

Iraq is well-known for long hours of sunshine, studies have shown that Baghdad (the capital of Iraq) alone receives more than 3000 hours of solar radiance per year. The solar intensity range changed from minimum value of 416 W/m^2 in January and maximum value of 833W/m^2 in June [5]. The monthly average sunshine hours for Baghdad city is illustrated in Fig. 1, it's indicates clearly that the sunshine hours are high all year long, which may be reached 350-360 h/month during summer season and 200-210 h/month during winter season. In Iraq, the deterioration of electricity with lack of maintenance and equipment's during the past 40 years are the most significant obstacles to supplying energy to consumers. Until now, the Electricity Ministry supply electricity to customers in most cities for 12 hours or less a day. Therefore the Iraqi peoples depend on personal and shared generators that operate with gasoline and diesel for their electricity demands [6].

Dust storms are a common occurrence in Iraq today due to the basin. The productivity and capacity of photovoltaic

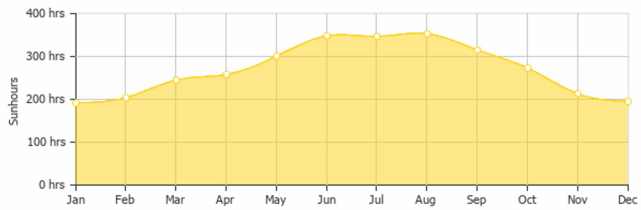


Fig. 1. Average monthly sunhours in Baghdad, Iraq [7].

modules are negatively affected by these storms, resulting in a clear decrease in the amount of electricity generated. Starting on April 1st, 2022 and continuing until April 12th, 2022, experimental tests were conducted. During this period, there was a dust storm that lasted three days in a row and has been considered as the worst storms on Baghdad. According to practical measurements, the intensity of solar radiation has decreased to 54.5% as compared to other days [8].

The PV system is negatively impacted by partial shading (PS) and it causes a reduction in power production from the panels. PS arises as a results of near buildings and trees shadows, tree leaves and clouds overhead. This will complicate the maximum power point tracking, and the conventional methods of maximum power tracking algorithms often fail during PSC. Consequently, various static and dynamic PV array reconfiguration algorithms have been developed [9]. Under PSC the PV system generated power will be less as compared with required power because of different irradiations levels falling on it [10]. The effect of PS on PV system can be minimized by employing suitable arrangements of PV array configurations. According to the literature, the basic PV array reconfigurations including series-parallel (SP), Total-cross-tied reconfiguration (TCT), Bridge-link reconfiguration (BL), and Honey-comb reconfiguration (HC) are available [11, 12]. Among these reconfiguration schemes, TCT has maximum power under the same conditions of partial shading [13]. The static reconfiguration methods such as (Su Do Ku, Magic Square (MS) technique, Dominance square, Zig-zag technique, Non-Symmetrical reconfiguration, Competence square, Shade dispersion physical array relocation (SD-PAR), Futoshiki puzzle technique, Skyscraper technique, Odd-even reconfiguration technique) are based on relocating shaded panels to equalizing the row current [14]. In the Zig-Zag technique, starting from the TCT configuration the PV panels of the first row are rearrange as the diagonal element. The other PV panels are rearrange in a row wise manner. The PV panels are rearrange such that panels in alternate columns are arranged in the same direction as in a Zig-zag pattern [13].

This paper proposed a new reconfiguration technique to enhance maximum power generated from PV array. In this study, a 3×22 PV array size is considered which is designed in [5] to supply power to the laboratories of the department of electronic and communications engineering in Al-Nahrain University, Baghdad, Iraq. The new reconfiguration performance compares the maximum power point (MPP), Fill Factor (FF), Mismatch Power Loss (MPL), and Efficiency (η) of the PV array with the (SP, TCT, and Zig-zag technique) reconfigurations methods. Apollo Solar Energy PV Module ASEC-320G6M is used in this study [15].

II. Electrical Demand and PV Array

Fig. 2 shows the department building of electronic and communications engineering at Al-Nahrain University and it contains 4 laboratories (Electrical and Electronic Circuits lab, Digital Electronics lab, Communications lab, and Postgraduate Students lab). The average daily load demand for these laboratories was calculated in [5] and it was 100968 Wh/day. The Pvsyst6 software package is used to design the PV array which can be used to supply electrical power to the laboratories. However, the simulation results from the Pvsyst6 software show that (3×22) PV panel with 320W type can be used to supply the electrical power to those laboratories. It was assumed that the laboratories are fully operational during the work hours (from 8:30 am - 2:30 pm), excluding Illuminations and air-conditioning equipment's.

Fig. 2. Electronic and Communications engineering department building.

The proposed location for installing the PV array is on the surface of the building. The array will be partially shaded during the day due to the presence of other nearby buildings and the clouds in the winter, therefore the process of reconfiguration of the PV panels is important to reduce the effect of this shading on the electrical energy produced.

III. PV Array Reconfigurations

The reduction of the losses due to partial shading conditions could be achieved through active or passive reconfiguration techniques. The passive reconfiguration techniques uses passive components such as diodes, on the contrary the active reconfiguration techniques uses active components like transistors [16]. Another passive method involves altering PV array interconnections [17]. The (3×22) PV arrays can be interconnected using basic PV array reconfigurations in SP, BL or TCT reconfigurations as shown in Fig. 3.

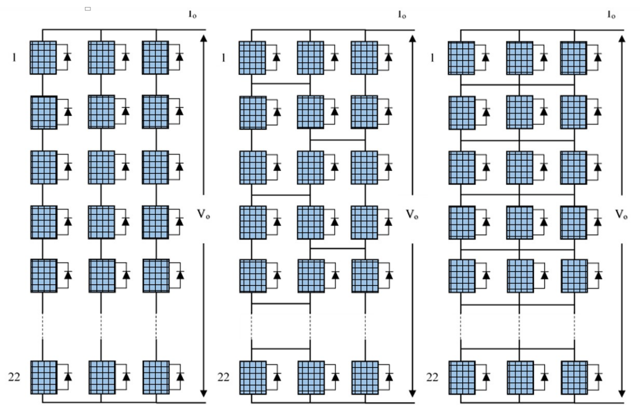


Fig. 3. (3×22) PV array reconfigurations (a) SP (b) BL (c) TCT.

The desired output power can be extracted by the solar PV system through different array reconfigurations. Due to long series strings, the SP reconfiguration is susceptible to uncertainty in solar radiation [17]. The SP structure has advantages such as being relatively simple and convenient to install [18]. For TCT reconfiguration, in the first step, all the PV panels in each row are connected in parallel, then the rows of the array are connected in series. This total cross-tie makes the PV panels in each row interconnected to each other and hence the mismatch losses will be minimized. This reconfiguration will reduce the multiple peak effect due to PSC [18]. As there are greater number of interconnection and cross ties in array of large size the wiring losses are more in TCT also there is difficulty in fault detection, the TCT tie connections are reduced to half in the BL reconfiguration [19] [20].

The TCT reconfiguration reduces the mismatch losses in case of partial shading effect and therefore the maximum power generated is larger when compared to other conventional reconfigurations such as SP, BL and HC [14]. In static reconfiguration methods the PV panels are rearrange in order to dispersed the shade and make the difference of row current approximately equal. One important type of static reconfiguration is the Zig-zag reconfiguration. In this technique, the PV panels in the first row of the TCT are rearrange as the diagonal element. The other PV panels are rearrange in a row wise manner. However, Fig. 4 shows the pattern structure of 3 × 22 PV panels using TCT and Zig-zag technique. The authors in [13] prove that the Zig-zag technique reduces the mismatch power losses due to PSC and increase the generated power when compared with the TCT structure. Were each row

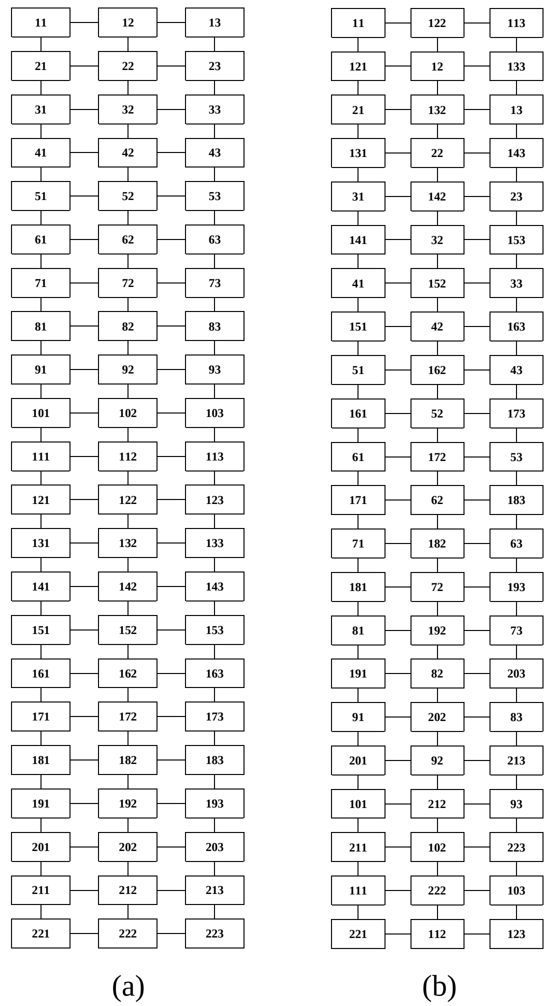


Fig. 4. Pattern structure of 3×22 array (a) TCT (b) Zig-zag.

is filled with numbers from 1 to 22 and each column is filled with numbers from 1 to 3. Therefore the PV panel number 173 is located in row number 17 and column number 3 and so on.

The power losses due to partial shading are dependent on the location of shaded modules in the array [21]. Therefore, if the PV panels on the same row at PSC are connected into different parallel circuits and the modules in the same column are rearranged in different locations then this will cause the partial shading to rearrange into different locations. This will improve the maximum generated power. Therefore, in this paper a new PV reconfiguration technique based on rearrange the PV modules in the array is proposed and tested using

MATLAB/Simulink for the (3 × 22) PV array designed in [5] as shown in the following section.

IV. Proposed PV Reconfiguration

The proposed technique based on rearrange the odd and even row number of the PV modules in each column in ascending and descending order respectively. This rearrangement will cause the partial shading to rearrange into distant places and improve the maximum PV array power point (MPP) and can be applied to PV arrays of any dimension. The proposed method is named Row Odd Even reconfiguration (ROE) and the following steps describe how to connect the PV modules using this method:

1. The PV modules are connected first in the conventional TCT reconfiguration.
2. The second column of the PV array is shifted down by 1 unit and the third column is shifted down by 2 units and so on.
3. For each column the odd row numbers are arrange in ascending order while the even row numbers are arrange in descending order.

Fig. 5 shows the ROE pattern structure of the (3 × 22) PV array.

To prove the significance of the proposed reconfiguration technique, a model of the PV arrays is constructed using MATLAB platform for the pattern structure shown in Figs. 4 and 5 using the Apollo Solar Energy PV Module ASEC-320G6M. The model was tested at different shaded conditions. The maximum power point (MPP), mismatch power losses (MPL), maximum power fill factor (FF), and efficiency (η) of the proposed array configuration is being compared with the conventional reconfiguration techniques such as SP, TCT and the Zig-zag static technique and the I-V and P-V characteristics and results are shown in the following sections. Table I shows the PV Module ASEC-320G6M parameters.

TABLE I.
PV Module ASEC-320G6M Parameters

Parameters	Values
Maximum power (PM) at STC	320 W
Voltage at maximum power (VMP)	35.96 V
Current at maximum power (IMP)	8.9 A
Short-circuit current (ISC)	9.27 A
Open–circuit voltage (VOC)	45.18 V
Module area	1.96 m^2

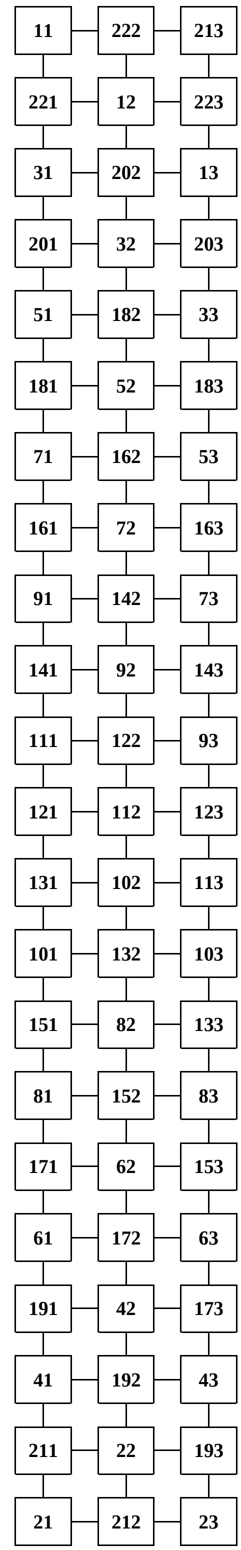


Fig. 5. Pattern structure of 3×22 array using ROE.

V. Performance Measures of the PV Arrays

The following performance parameters are used to test the system for effectiveness of the new array reconfiguration.

A. Maximum Power Point (MPP)

This is a crucial parameter for the PV array as it gives the maximum power obtained from the PV array at a certain condition. Generally, the peak point of the characteristic is the point at which the maximum power can be generated, but in the cases of partial shading several local peaks may be obtained. The global peak point (P_{GMPP}) is the highest amount of power that can be extracted.

B. Missmatch Power Loss (MPL)

As commonly known, a PV array have N_p number of parallel and each parallel string contain of Ns modules in series. As a result, the array's nominal power will be,

$$P_{array} = \Sigma_{i=1}^{n} P_i \tag{1}$$

where $n = N_p N_s$ and P_i represents i^{th} PV module output power. The output generated power of the array is less than the value calculated in the above equation. The difference between the maximum output generated power and the sum of the maximum powers of the PV panels in the array is called the mismatch power losses [22]. The MPL can be calculated as [23]:

$$MPL = \frac{P_{array} - P_{GMPP}}{P_{array}} \times 100\% \tag{2}$$

C. Maximum Power Fill Factor (FF)

A parameter that indicate or define the total performance of a PV panel when the shadow moves and shading effect increasing on the PV array module is the FF. The FF value is computed by dividing the maximum power point (MPP) over the multiplication of the open circuit voltage (V_{OC}) and the short circuit current (I_{SC}) as follows [24]:

$$FF = \frac{MPP}{V_{OC} \times I_{SC}} \times 100\% \tag{3}$$

For better performance of the array it's concluded that FF should be nearer to 100%.

D. Efficiency (η)

The efficiency of the PV array is calculated by dividing the PV array generated power over the amount of incident solar irradiation which is delivered by the sun as follows [25]:

$$\eta = \frac{MPP}{I \times A} \times 100\% \tag{4}$$

where I is the solar irradiance per unit area and A is the area of the PV array on which solar irradiance falls.

VI. Partial Shading Patterns

In order to analyse the overall performance of the array reconfigurations (SP, TCT, Zig-zag, and ROE) under partial shading conditions, different PSC are considered as shown in Fig. 6. Five different partial shading conditions are applied for each type the above mentioned reconfigurations and various irradiance levels are taken (1000 W/m^2, 700 W/m^2, 500 W/m^2, 300 W/m^2, and 100 W/m^2) at temperature of 25^{o}C.

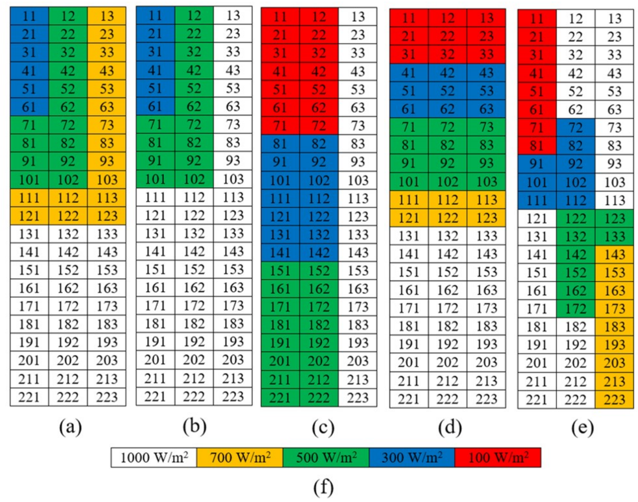


Fig. 6. Partial shading conditions for SP and TCT (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5.

The above figure shows the partial shading arrangement for the SP and conventional TCT configuration while Figs. 7 and 8 shows the rearrangement of the partial shading on the PV modules using Zig-zag and ROE respectively.

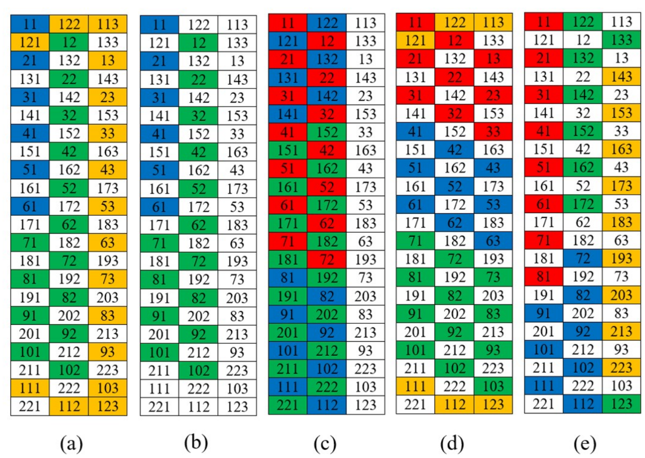
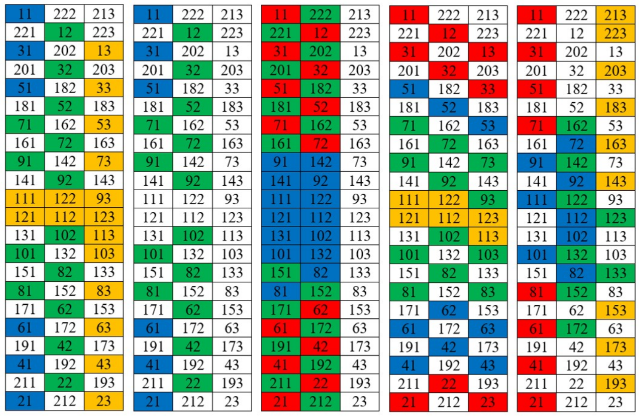


Fig. 7. Rearrangement of the PSC using Zig-zag reconfiguration (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5.



(a) (b) (c) (d) (e)

Fig. 8. Rearrangement of the PSC using ROE reconfiguration (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5.

It is clear from Figs. 7 and 8 that the Zig-zag and ROE static reconfiguration disperse the shaded panels all over the PV array on the contrary of the SP and TCT reconfigurations shown in Fig. 6 which keeps shaded panels in place. Therefore, the generated power from the PV array using the Zig-zag and ROE reconfiguration techniques will be more than that obtained from the SP and TCT reconfigurations.

VII. Simulation Results and Discussion

The proposed reconfiguration technique (ROE) with the SP conventional TCT and the Zig-zag PV array reconfiguration techniques were modelled and simulated using MATLAB/Simulink. Fig. 9 shows the Apollo Solar Energy PV Module ASEC-320G6M characteristic at 25^{o}C and (100, 300, 500, 700, and 1000 W/m^2) irradiation levels. The maximum power at these irradiances equal to (31.1, 96.8, 162.1, 225.9, 318.2 W) respectively.

Figs. 10 shows the P-V characteristics for the reconfiguration techniques (SP, TCT, Zig-zag and ROE) for the five cases of PSC presented in Figs. 6, 7, and 8 respectively.

Table II shows that the performance parameters (MPP, MPL, FF, and η) for the reconfiguration techniques under each test condition. From Fig. 10 and the values in Table II it is clear that both the ROE and Zig-zag reconfiguration techniques generate higher output power than SP and TCT reconfiguration techniques. However, the SP reconfiguration generates comparatively lower output power in all test conditions while the ROE reconfiguration generates higher output power in most tests. Under uniform irradiance condition an equal amount of generated power are given by the all considered PV arrays reconfigurations. At corner shading (case 2) the generated power form ROE and Zig-zag are the same.

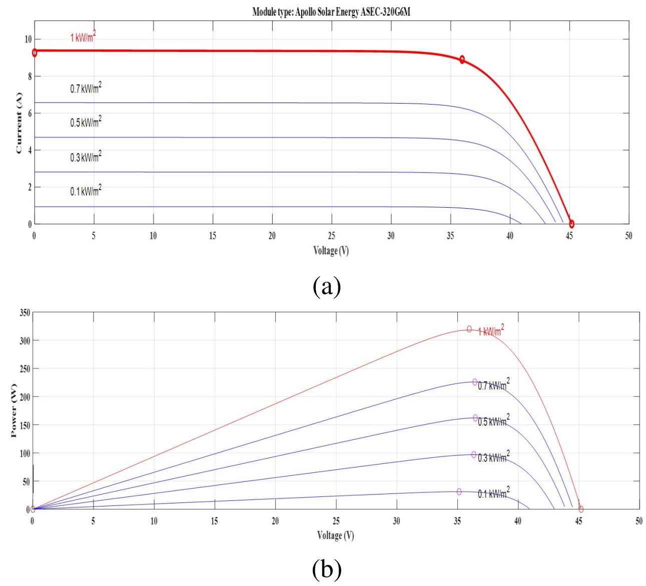


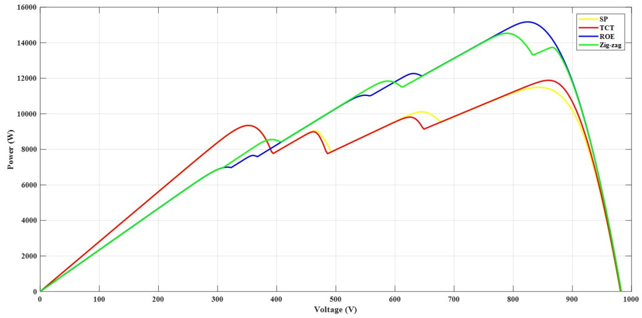
Fig. 9. ASEC-320G6M panel (a) I-V (b) P-V characteristics.

VIII. Conclusions

The new proposed reconfiguration technique which introduced in this paper presents better results when comparing to the SP, TCT and Zig-zag array reconfiguration techniques. The new static rearrangement technique named ROE and it is proposed to increase a (3×22) PV array output power when affected by different partial shading conditions. This proposed technique based on rearrange the odd and even row number of the PV modules in each column in ascending and descending order respectively. This rearrangement will cause the partial shading to rearrange into distant places and improve the maximum power point (MPP). The arrangement of modules of the PV array in the new reconfiguration technique is fixed. The new reconfiguration performance is investigated in details by simulation on MATLAB/Simulink model for a 3×22 PV array for different partial shading conditions. In the simulation the performance parameters (MPP, MPL, FF, and η) of the ROE technique is compared with other reconfiguration such as SP, TCT and Zig-zag under five different partial shading conditions. The simulation results show that the ROE technique produce maximum output generated power and therefore it can increase the output power generated from the PV array under different shading conditions. Also, the results show that ROE reconfiguration contains minimum power losses, maximum efficiency and increasing the fill factor of the PV Array.

Conflict of Interest

The author has no conflict of relevant interest to this article.



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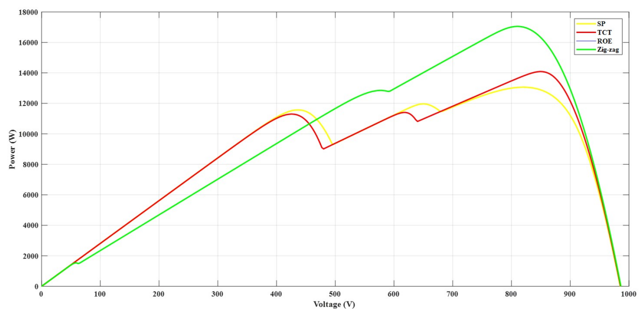

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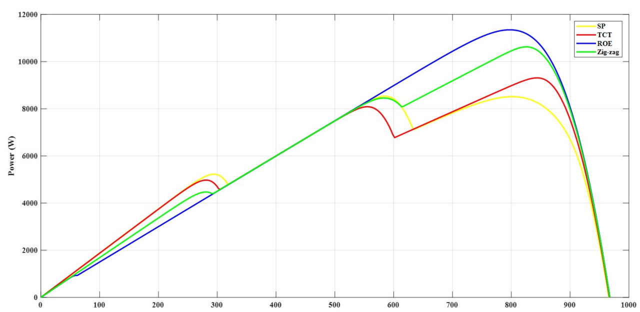

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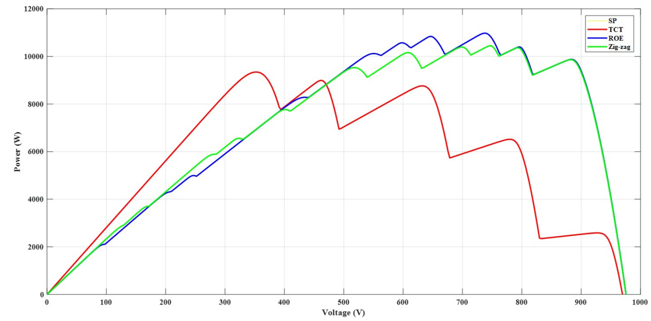

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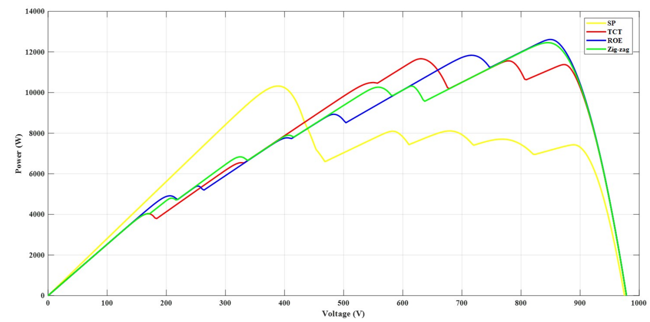

(e)

Fig. 10. (P-V) characteristics of the (SP, TCT, Zig-zag, and ROE) for (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5.

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TABLE II.
PERFORMANCE PARAMETERS FOR DIFFERENT ARRAY RECONFIGURATIONS

Case 1						
	VOC (V)	I_{SC} (A)	MPP (W)	MPL (%)	FF (%)	η (%)
SP	981.3	28.2	1.1492×10^4	28.22	41.53	11.73
TCT	981.6	28.2	1.1886×10^4	25.76	42.94	12.13
Zigzag	982.6	23.5	1.4533×10^4	9.23	62.94	14.83
ROE	982.7	23.5	1.5173×10^4	5.23	65.7	15.48
Case 2						
	VOC (V)	I_{SC} (A)	MPP (W)	MPL (%)	FF (%)	η (%)
SP	985.1	28.165	1.3062×10^4	25.31	47.08	12.16
TCT	985.6	28.165	1.4088×10^4	19.44	50.75	13.12
Zigzag	986.3	28.155	1.705×10^4	2.5	61.4	15.87
ROE	986.3	28.155	1.705×10^4	2.5	61.4	15.87
Case 3						
	VOC (V)	I_{SC} (A)	MPP (W)	MPL (%)	FF (%)	η (%)
SP	965.9	18.7	8.5332×10^3	25.05	47.24	12.23
TCT	966.8	18.7	9.3098×10^3	18.22	51.49	13.34
Zigzag	967.3	16.9	1.0625×10^4	6.67	65	15.23
ROE	967.5	16.9	1.1348×10^4	0.32	69.4	16.26
Case 4						
	VOC (V)	I_{SC} (A)	MPP (W)	MPL (%)	FF (%)	η (%)
SP	969.6	28.2	9.3448×10^3	33.24	34.18	10.89
TCT	969.6	28.2	9.3448×10^3	33.24	34.18	10.89
Zigzag	975.5	23.5	1.0452×10^4	25.33	45.59	12.18
ROE	975.7	23.5	1.0978×10^4	21.57	47.88	12.79
Case 5						
	VOC (V)	I_{SC} (A)	MPP (W)	MPL (%)	FF (%)	η (%)
SP	975.1	28.2	1.032×10^4	30.52	37.53	11.32
TCT	978.26	25.4	1.1664×10^4	21.47	46.94	12.8
Zigzag	978.31	25.4	1.2458×10^4	16.13	50.13	13.67
ROE	978.36	25.4	1.2614×10^4	15.08	50.76	13.84
Case 6 (uniform shading at 1000 W/m^2)						
	VOC (V)	I_{SC} (A)	MPP (W)	MPL (%)	FF (%)	η (%)
SP	994.6	28.165	2.106×10^4	0	74.97	16.3
TCT	994.6	28.165	2.106×10^4	0	74.97	16.3
Zigzag	994.6	28.165	2.106×10^4	0	74.97	16.3
ROE	994.6	28.165	2.106×10^4	0	74.97	16.3

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