Fuzzy Based Reconfiguration Method Using Intelligent Partial Shadow Detection in PV Arrays[*]

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Abstract

Photovoltaic (PV) systems are the most commonly used methods. PV systems have the most potential and efficiency between the species of renewable energy. However, this method can be subjected to a loss of energy gain when shading occurs on the PV panels. To overcome this negative situation, a reconfiguration process in the PV systems has been developed. Through this method, the power losses caused by the shading of the panel on the system are attempting to be minimized . Without any change in the physical location of the pre-shading panels, the panels are co nfigured with electrical connectors. In this study, a new efficient and intelligent reconfiguration method is proposed. The short-circuit current values of the PV panels are detected using current sensors. Short-circuit current values vary in proportion to the shadings that occur on the panels. A fuzzy calculation is carried out taking the current values into account as the system input parameters. The optimal connection structure is detected by using the fuzzy output values. The result is then applied to the system by switching the matrix circuit. The proposed method has been tested in different shadowing conditions and has been seen as a gain ratio. Experiments performed in real-time availability have confirmed the suitability of the method for different sized systems.

Keywords: PV Arrays, Shadow Detection, Reconfiguration, Partial Shading Diagnosis, Fuzzy Logic, Switching Matrix.

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1. Introduction

Nowadays, the amount of non-renewable energy sources demand and rising fuel prices have led to a turn to renewable energy sources. Hence, researchers are working to produce energy using renewable natural resources. In this way, they are aiming to meet the growing energy demand, be environmentally friendly and reduce the cost. One of the most appropriate renewable energy sources is solar energy. Electrical energy is obtained by converting solar radiation in PV systems. While obtaining this type of energy, some disadvantaged situations may occur (e.g., partial shading may occur in PV arrays because of clouds, birds, trees or contamination) and the solar radiation received by a PV panel can drop in value . As such, the amount of power given by a panel decreases because of the shading[1]. Two methods have been developed to overcome the negative effects of shading: maximum power point tracking (MPPT) and reconfiguration[2]. In the MPPT approach, the main aim is tracking the maximum power point on a PV curve that is obtained by using the present system values (e.g. current, voltage and power). However, the applicability of this method is not appropriate for all PV arrays and it is the only system-specific working method [3,4,5,6,7,8,9,10]. This approach is also unable to provide sufficient efficiency, as it cannot obtain sufficient power and takes so much time.

In the second approach, the reconfiguration aims to find the best connection structure that obtains the maximum power point in the PV system. The reconfiguration process uses a fixed panel, an adaptive panel and a switching matrix circuit. The system provides the opportunity to work with a dynamic structure[11]. Many studies have investigated the reconfiguration[12,13,14,15]. In some of these studies, in the reconfiguration process, mathematical calculations and various input parameters are used. The reconfiguration process proposed by Liu et al.[12] is shown in Fig. 1. In this study, the voltage and current values taken from the panels are used. El-Dein et al.[13] calculated the index value of the radiation level compliance. These methods are difficult and time-consuming because of the calculation complexity and the need for extra calculations.

In some of the reconfiguration methods, changes associated with the electrical structure of the PV cell have been proposed. In such methods, the hardware used in system made the system more complex. As such, there was a reduced efficiency in obtaining the values of these elements in the reconfiguration process. Velasco et al.[15] used the EAR (Electrical Array Reconfiguration) approach and proposed a mathematical expression to minimize the difference between the radiation levels on the arrays by using the switches. In another study dealing with radiation values of PV arrays[16], a reconfiguration is provided by the Su Do Ku method. Su Do Ku is a method designed by assigning logical values to PV arrays. It aims to obtain the maximum power from the system in cases of partial shading without making any changes in the electrical connections of the PV arrays. The shading values are distributed to different regions to get the same radiation on the same sub-modules.
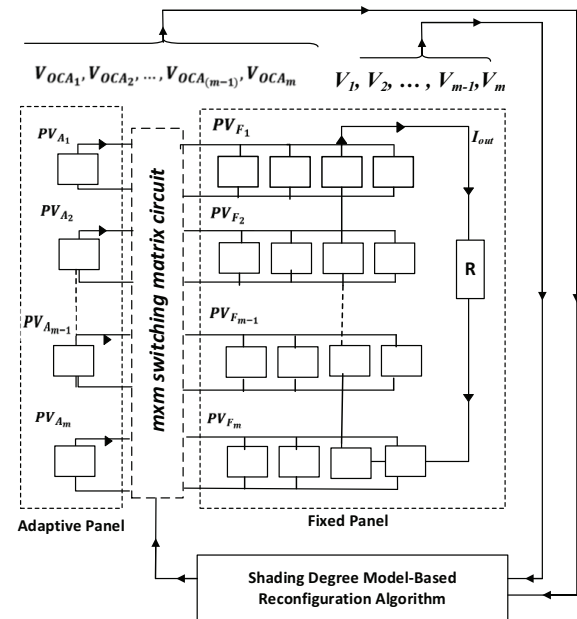

Fig. 1. Reconfiguration process [12].

While the proposed approaches can be applied to small sized systems, they cannot be applied to large sized systems. [17] calculated all of the possible connections for arrays and found the best one among them. However, the permutations and sorting operations used negatively affected the performance of the system. In another study[18], the bubble sort algorithm was used. When this method is applied in large sized systems, the process time will be increased, even though it had an efficiency in small sized systems. In Nyugen et al.[19], two methods were proposed to find the maximum power from the

arrays. Experimental operations were applied for a small sized PV system. When we consider this approach for more PV arrays, it will take more running time.

Reconfiguration is a method that is developed to increase the output power of a PV system that decreased in the case of partial shading. This method mainly consists of basic blocks: fixed panel, adaptive panel and a switching matrix circuit. The fixed panel has more PV cells and is the main part of the system. It is structured with one of the connection types of the S&P (Series-Parallel), TCT (Total-Cross Tied) and BL (Bridge-Linked), as illustrated in Fig. 2. It does not undergo any changes during the process and is always fixed. The first part, the fixed PV panel part, consists of mxn PV panels (m sub-modules, consisting of n cells). The arrays in the fixed panels are F_1, F_2,…, F_m. The second main part, the adaptive panel, consists of an m PV panel, A_1, A_2,…, A_m. There is also a switching matrix circuit that provides the connection between the adaptive panel and the fixed panel. As illustrated in Fig. 3, each switch in this circuit is designed, as any PV array in an adaptive panel will be connected to an array in the fixed panel.
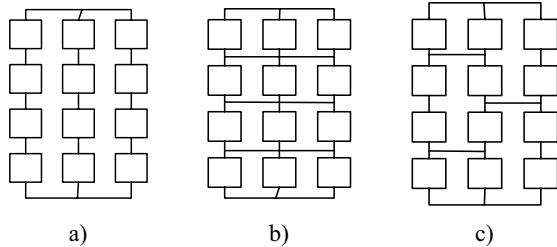

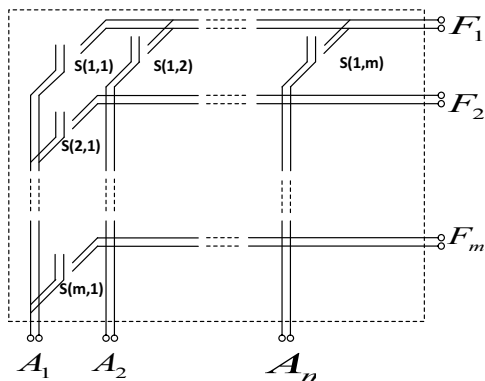Fig. 2. Connection type of fixed panel a) S&P b) TCT c) BL

Fig. 3. Switching matrix circuit

The reconfiguration approach is aimed at determining the best connection structure that provides the maximum power for the system by the processing values from the adaptive and fixed panels. The obtained connection information is applied to the system by a switching matrix circuit. The PV system will become the dynamic mode of the operation with this method. A graphic that shows the power efficiency obtained with the reconfiguration method is illustrated in Fig. 4.
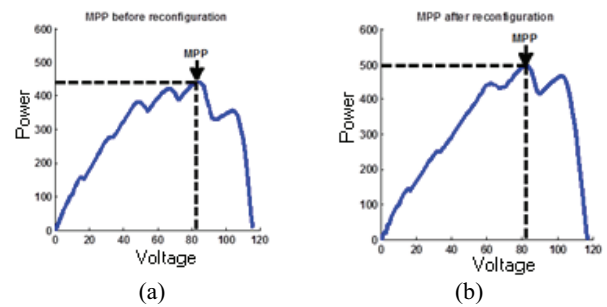

(a)   (b)

Fig. 4. MPP variation for a reconfiguration in the same PV array

In this study, a fuzzy partitioning based artificial approach for a reconfiguration in PV arrays has been proposed. For the fixed panel structure, a TCT connection type is used. The proposed algorithm takes the radiation and current values from the adaptive panel and the fixed panel as input parameters. The detected values are transmitted to a control and decision unit after processing the fuzzy calculations. The results taken from the unit are sent to the switching matrix circuit. The system has the optimum connection structure to obtain the maximum power. Large and small sized PV systems both have short reply times with this algorithm. In addition, the system will work at the maximum power point.

2. Proposed Approach

The reconfiguration is an important method for providing the maximum performance on a PV system. In performing the method, a major step is determining the optimal connection structure. This step should be as accurate and as quick as possible, especially in large sized systems. In this study, a very efficient algorithm that can be applied to real time systems is proposed. The algorithm has a fuzzy partitioning based artificial approach. The short circuit currents obtained from the adaptive and fixed panels (I_{sc}) are transmitted to a fuzzy control unit. Here, the fuzzy partitioning operation is

done. The optimal connection structure is then determined and the result is applied to the arrays by the switching matrix circuit. A block diagram illustrating proposed approach is given in Fig. 5.
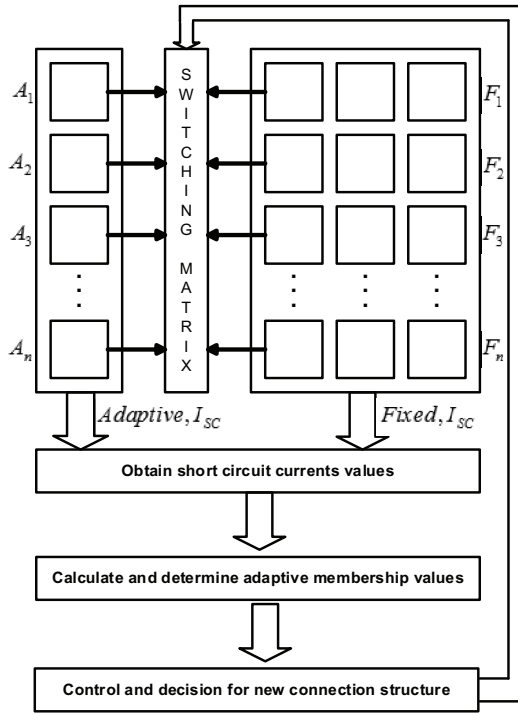

Fig. 5. Block diagram for proposed approach

In the proposed approach, a different use of fuzzy technique is proposed. Typically, fuzzy logic that used in situations involving uncertainty, is used to determine the optimal panel layout in reconfiguration problem. The reason for using this technique in large-scale PV systems in the reconfiguration process is to identify the best-panel layout quickly. For this purpose, this radiation values based on the value of the short circuit currents are determined and according to fuzzy values determined by the proposed approach radiation values are grouped. These values grouped for adaptive and fixed arrays, matched appropriately and new optimal panel layout is obtained.

A. Obtaining short circuit currents: When a PV array is exposed to partial shading conditions, the output short circuit current value of each module will change, because the radiation values on the PV panels change. In the proposed method, our fuzzy partitioning based algorithm is taking the short circuit current values as

input parameters. Both numbers of sub-modules in the adaptive panel and fixed panel (n) are obtained as short-circuit current values. The obtained values are sent to the next unit for calculating the fuzzy measurements.

B. Fuzzy measurement with adaptive values: The obtained connection structure that provides the maximum power from the system in the case of the partial shading of a PV system has an important role in the availability of the system. Therefore, this step in the reconfiguration approach can provide a higher amount of power. For this step, an efficiency and applicable fuzzy partitioning method solution is used for less complexity in the calculations [20,21,22,23]. The proposed system is a single-input single-output fuzzy structure. Therefore, input and output values are determined as a result of studies and observations. Radiation levels as a result of these observations are grouped into five different groups. These are, respectively, very low (VL), low (L), medium (M), high (H) and very high (VH) values. Especially, the most important advantage of the proposed approach, the optimal order on large-scale PV panels can be detected without any calculations. The method of the partitioning process, rather than being determined as constant, has been developed with a dynamic structure. For the different short-circuit current, the membership values may be illustrated as different structures. A flow chart of the method is shown in Fig. 6.
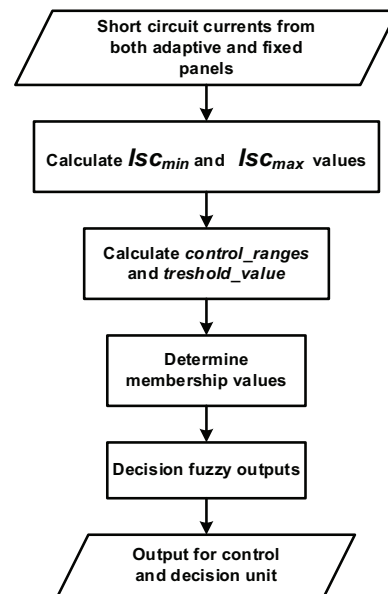

Fig. 6. Fuzzy measurement with adaptive values

The amount of shading on a PV panel consists of radiation values in the range of 0-1000 W/m2. The value produced in response to this radiation is the amount of short-circuit current and is between 0-3.8A. However, because each sub-module in the fixed panel contained more than one PV panel, the obtained short circuit current values will be out of the expected value range. Therefore, the normalization of the values obtained from the fixed panel must be provided. The equation for the normalization process is given in Eq. (1). Some irradiance and short circuit current values obtained from the PV arrays are presented in Table 1.

$$I_{SCavg} = \sum_{i=1}^{m}\left(\sum_{j=1}^{n} I_{i,j}\right)\bigg/ n \qquad (1)$$

By using all of the short circuit current values ($I_{sc}A$ and I_{SCavg}), a minimum value and a maximum value have calculated. For this calculation, Eq. 2 and 3 are used. $I_{sc}A_i$ is the short circuit current from the adaptive panel. $I_{sc}F_i$ is the short circuit current from the fixed panel, I_{SCmin}, is the minimum current value, I_{SCmax}, is the maximum current value and n is a count of sub-modules.

$$\min[min(I_{sc}A_i), min(I_{sc}F_i)] = I_{sc_{min}}, i \in \{1, 2, \dots, n\} \qquad (2)$$

$$\max[max(I_{sc}A_i), max(I_{sc}F_i)] = I_{sc_{max}}, i \in \{1, 2, \dots, n\} \qquad (3)$$

The next step requires determining the range that the membership values frequently exist in. For this procedure, a control range and a threshold value are calculated by using Eq. 4 and 5. The lower limit is *cntrl_min*, while the upper limit is *cntrl_max.* The threshold value is *threshold_value,* and the count of expected membership value is the *number_of_membership (NoM);* and k is a constant and is determined experimentally.

$$cntrl_{min} = [I_{sc_{min}} - \frac{I_{sc_{min}}}{Nom}, I_{sc_{min}} + \frac{I_{sc_{min}}}{Nom}] \qquad (4)$$

$$cntrl_{max} = [I_{sc_{max}} - \frac{I_{sc_{max}}}{Nom}, I_{sc_{max}} + \frac{I_{sc_{max}}}{Nom}] \qquad (5)$$

$$treshold\_value = round((n * 2) * k) \qquad (6)$$

When these values are considered, the range that the membership values are frequently in are calculated as illustrated in the pseudocode below. *count_min*, shows how many short circuit current values are in the range of *cntrl_min*. The value of *count_max*, shows how many short circuit current values are in range of *cntrl_max*.

Table 1. Irradiance and short circuit currents values

	Adaptive Arrays			Fixed Arrays				
No	Irradiance (W/m2)	I_{SC} (A)	No	Irradiance (W/m2)			I_{SC} (A)	$I_{SC\ AVG}$
A_1	300	**1.138**	F_1	750	850	900	9.486	**3.162**
A_2	300	**1.138**	F_2	650	750	500	7.209	**2.403**
A_3	300	**1.138**	F_3	600	1000	600	8.347	**2.782**
A_4	800	**3.035**	F_4	400	400	400	4.553	**1.517**
A_5	700	**2.656**	F_5	500	500	500	5.691	**1.897**
A_6	600	**2.277**	F_6	600	600	600	6.83	**2.276**
A_7	900	**3.415**	F_7	700	850	900	9.266	**3.088**
A_8	850	**3.225**	F_8	850	850	900	9.865	**3.288**
A_9	1000	**3.794**	F_9	850	900	1000	10.055	**3.351**

Step 1. Calculate $I_{sc}min$ and $I_{sc}max$
Step 2. Calculate control ranges and threshold value
Step 3. If ($count_{min} \geq threshold\_value$)
                 start_value = $I_{sc}min$
                 Goto Step 4
        Else
                 $I_{sc}min$ = the next minimum value
                 Goto Step 2

Step 4. If ($count_{max} \geq threshold\_value$)
                 end_value = $I_{sc}max$
        Else
                 $I_{sc}max$ = the previous maximum value
                 Goto Step 2
Step 5. Get *start_value* and *end_value*

The start_value and end_value is the start point and end point, respectively, of the fuzzy measurements. This range is labeled with fuzzy labels by dividing the count of the membership values. When Table 1 is considered and constant, k, is 0.3, the membership values are obtained as shown in Fig. 7. Membership labels are very low (VL), low (L), medium (M), high (H) and very high (VH).
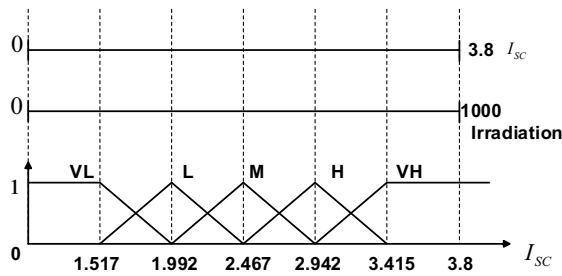

Fig. 7. Relationship between fuzzy measurements and I_{SC}

In Fig. 8, the membership values for each adaptive array are shown. The shades on this figure are illustrated as radiation values. When calculating the membership value of the fuzzy labels, we should determine the placement of the current value on the membership functions (e.g., 0.8L, 0.2M). The bigger value is the point value (0.8L); it will be the membership value to take for the current value. If both point values are the same, we would take the larger membership values. In Fig. 9, a membership value of 1.138A is illustrated.

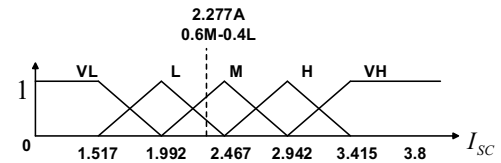Fig. 8. One example of adaptive and fixed arrays

Fig. 9. Membership of a short circuit current value

C. Control and Decision: The determined short circuit current values of the adaptive and fixed panels are sorted from very low (VL) to very high (VH). A crossing operation is applied to the sorting values as the minimum value of the fixed panel is mapped to the maximum value of the adaptive panel. For example, an adaptive array panel with a VL value can be matched with a panel with the VH values in the fixed array. A block diagram showing this condition is shown in Figure 10. In this way, the radiation values of the sub-modules in the system is averaged and the optimal result are determined. A connection structure that is calculated with that approach is shown in Fig. 10.
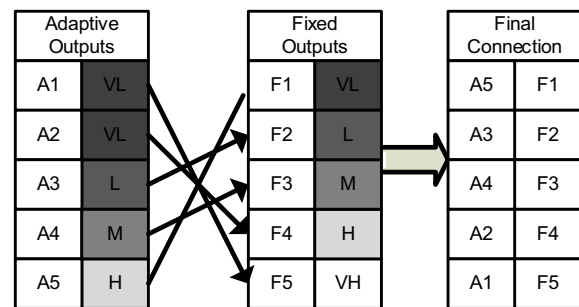

Fig. 10. An example of the control and decision

3. Simulation and Experimental Results

In this study, simulations are actualized to overcome the disadvantages of the partial shading conditions on the PV arrays by testing the different sized arrays and different partial shading conditions. The characteristic attributes of the PV panels used in the simulations are given in Table 2. The input parameters used for the proposed algorithm are taken from the nine sub-modules. These radiation and current values are given in Table 1. The membership values of the state adaptive and fixed panels are illustrated in Table 3.

Table 2. Characteristics of PV Panel

Description	Value
Size of fixed arrays	9x3
Size of adaptive arrays	9x1
Minimum irradiance value of panels	$0 \ W/m^2$
Maximum irradiance value of panels	$1000 \ W/m^2$
Minimum I_{SC} value of panels	0 A
Maximum I_{SC} value of panels	3.8 A
Temperature	25 ^{o}C
Maximum power (P_{MAX}) of panels	65 W

Table 3. Membership Values

	Adaptive Arrays			Fixed Arrays	
No	*Fuzzy Output*	*Fuzzy Groups*	**No**	*Fuzzy Output*	*Fuzzy Groups*
A_1	1.0 VL	VL	F_1	0.47 VH 0.53 H	H
A_2	1.0 VL	VL	F_2	0.87 M 0.13 L	M
A_3	1.0 VL	VL	F_3	0.66 H 0.34 M	H
A_4	0.8 H 0.2 VH	H	F_4	1.0 VL	VL
A_5	0.6 M 0.4 H	M	F_5	0.8 L 0.2 VL	L
A_6	0.6 M 0.4 L	M	F_6	0.6 M 0.4 L	M
A_7	1.0 VH	VH	F_7	0.3 VH 0.7 H	H
A_8	0.6 VH 0.4 H	VH	F_8	0.73 VH 0.27 H	VH
A_9	1.0 VH	VH	F_9	0.86 VH 0.14 H	VH

The columns titled *fuzzy output* in Table 3 are the points among the membership values measured as the fuzzy values. The column titled *fuzzy group* is determined by the membership value. The fuzzy group values are determined as discussed previously. This value is then sorted and applied to the cross process. The connection

structure before the reconfiguration and the final structure are illustrated in Table 4. The relationship between the irradiance values on the PV panels are given in Table 5. When considering this relationship, the total irradiance value of the connected arrays are closer, as compared to before the reconfiguration. The radiance values changed from [933 W/m^2 - 1917 W/m^2] before the reconfiguration to [1117 W/m^2 - 1533 W/m^2] after the reconfiguration.

Table 4. The connection structure before and after reconfiguration

Type of Array	Before Reconfiguration								
Adaptive	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
Fixed	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9
Type of Array	**After Reconfiguration**								
Adaptive	A_6	A_7	A_5	A_9	A_8	A_4	A_3	A_2	A_1
Fixed	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9

The two connection structures shown in Table 5 are actualized in the MATLAB environment. The obtained P-V and I-V graphics are given in Fig. 11 (a-b). As noticed in both of these figures, the proposed approach provides a larger power point than the conventional methods. However, the proposed approach does not contain any calculations to extend the process time. Hence, the system does not have the complexity and can actualize all operations in a minimum amount of time. The efficiency of the PV arrays will be at the maximum point. An experiment mechanism in 3x4 size is prepared for real-time testing of the proposed approach. A video is recorded by using this experimental setup and a camera. Then, the resulting full or partial shadings on the panels were determined by image processing algorithms implemented on the video image. An example scenario illustrating algorithm steps is presented in Fig. 12. In addition, the panel radiation values were obtained thanks to this algorithm and given to the fuzzy partitioning algorithm as input parameter. Finally, the results obtained from the proposed approach has been sent to the switching matrix. Thus it was determined the optimal panel layout. Connection layouts of before and after reconfiguration are given in Fig. 13-(a) and (b), respectively.

Table 5. Irradiance and short circuit currents values

Type of Array	Before Reconfiguration								
Adaptive Panel	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
Irradiance(A) (W/m^2)	300	300	300	800	700	600	900	850	1000
Fixed Panel	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9
Avg(Irradiance(F)) (W/m^2)	833	633	733	400	500	600	817	867	917
sum_of_irradiance(W/m^2)	1133	933	1033	1200	1200	1200	1717	1717	1917
	After Reconfiguration								
Adaptive Panel	A_6	A_7	A_5	A_9	A_8	A_4	A_3	A_2	A_1
Irradiance(A) (W/m^2)	600	900	700	1000	850	800	300	300	300
Fixed Panel	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9
Avg(Irradiance(F)) (W/m^2)	833	633	733	400	500	600	817	867	917
sum_of_irradiance(W/m^2)	1433	1533	1433	1400	1350	1400	1117	1167	1217

(a)

(b)
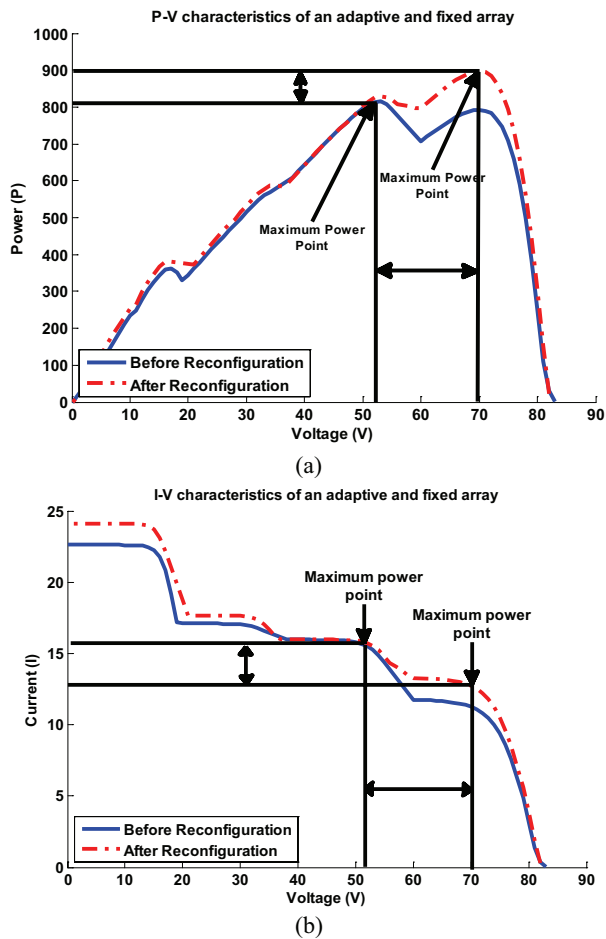
Fig. 11. P-V and I-V graphics for reconfiguration process

(a)   PV array with shading

(b)   HSV color space

(c)   Detection process
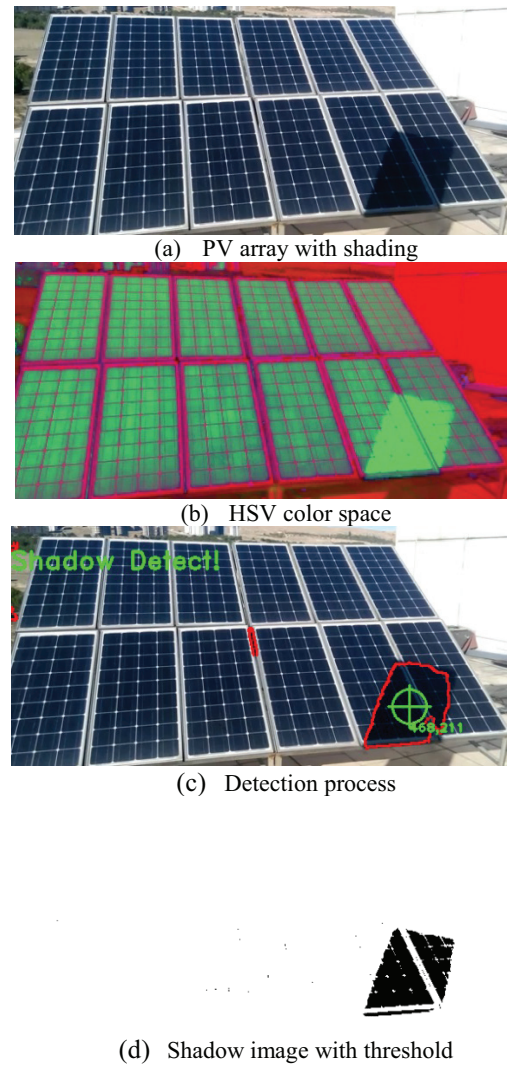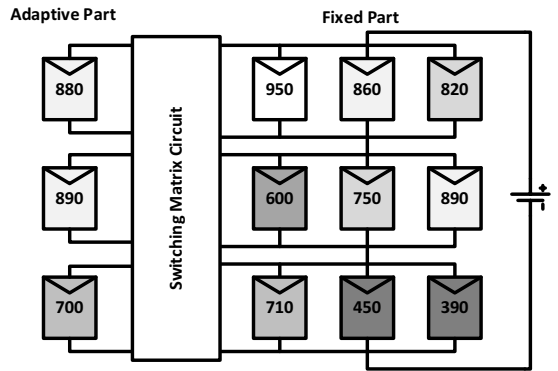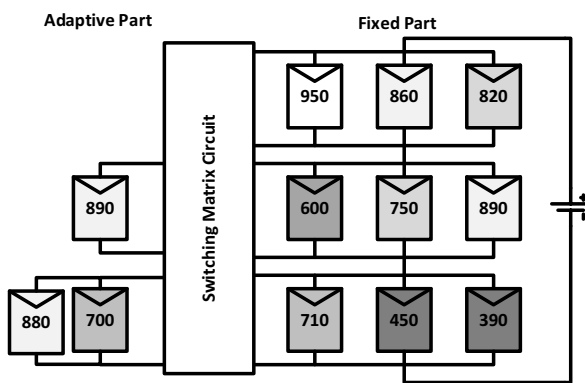

(d)   Shadow image with threshold

Fig. 12. Shadow detection for reconfiguration

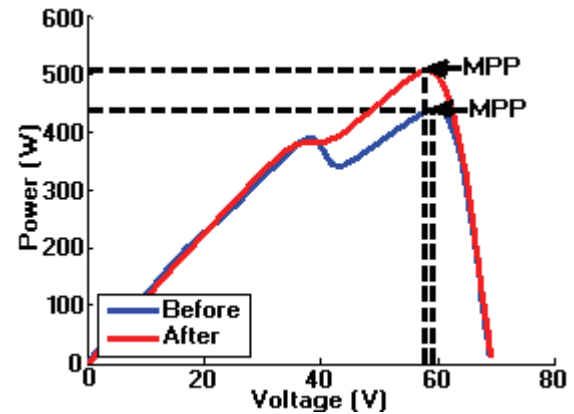(a) Configuration of PV array before reconfiguration
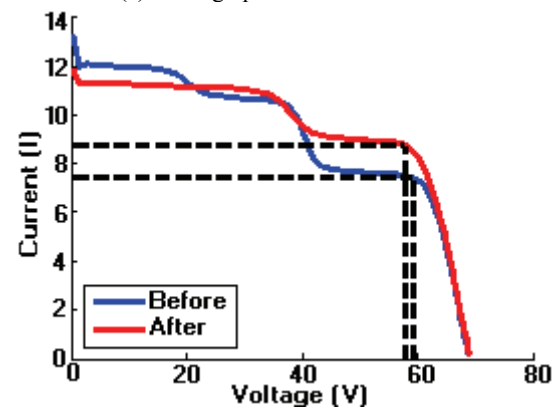

(b) Configuration of PV array after reconfiguration

Fig. 13. PV array configuration before and after the reconfiguration process

(a) P-V graphics for simulation results

(b) I-V graphics for simulation results

Fig. 14. P-V and I-V graphics

As can be seen from Fig. 13, the adaptive panel A_1 and A_3 are connected F_3 and F_1 is not connected to any adaptive panel. A_2 is connected to the F_2. The values of new connection layouts obtained by proposed fuzzy partitioning algorithm has measured by both MATLAB and oscilloscope in real-time. The results obtained in MATLAB for P-V and I-V changes, are also presented in Fig. 14-(a) and (b). Also, real-time measurement results obtained by the oscilloscope is shown in Fig. 15. According to measurements, the PV curve is provided a yield increase of approximately 15%. This change shows the results are given in Table 6.

Also, in this study, quitely efficient result are obtained in terms of the execution time. When the studies in the literature is analyzed, the selection of the optimal connection layout between possible connections of configurations obtained by switching matrix is taken more time. The comparison results of proposed approach and studies in the literature are presented in Table 7.
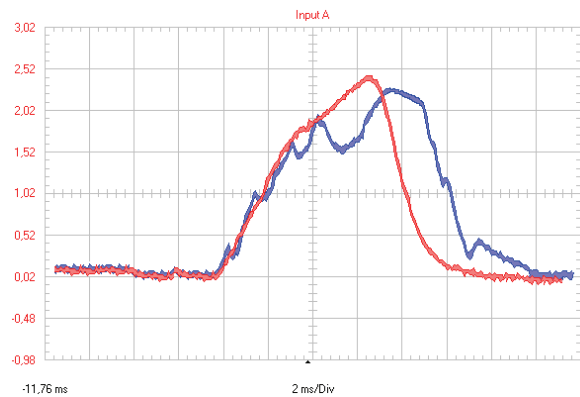

Fig. 15. Experimental results for P-V graphics before and after reconfiguration scenario

Table 6. The amount of change for PV panels

Description	Value
MPP value before reconfiguration (W)	439,7053
MPP value after reconfiguration (W)	506,7223
Power increasing (W)	67,017
Power increasing (%)	15,2413

Table 7. Computational complexity

Methods	Array Size		
	3x3	**5x5**	**7x7**
Model based method [12]	9 seconds	150 seconds	28800 seconds
Bubble-sort method [19]	18 seconds	450 seconds	100800 seconds
Proposed method	3.1 seconds	6.9 seconds	12.3 seconds

4. Conclusions

In this study, a fuzzy logic-based detection system for an optimal panel PV system is carried out. In the proposed approach, the short-circuit current value of the system through the current sensor was obtained. Afterwards, the current values were sent to the fuzzy calculation unit. In this unit, the short circuit currents are converted to radiation values and the panels are classified as parallel to the radiation values. The classified values, represents the shading degrees, are accelerated in the presence of optimal panel layouts with this classification process. The resulting output values are transmitted to the control decision unit. The final configuration is applied to the PV systems with the help of the switching matrix. This proposed approach provides energy efficiency on the PV curve of about 10%-15%.

The most important advantage of the fuzzy partitioning based reconfiguration approach is its ability to offer quick solutions for large PV systems. The classification of the panels, according to the short circuit current and radiation values, is the most important factor that allows the rapid detection. Another advantage of the proposed method is that it can operate independently of the type of connection.

Acknowledgement

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