Couple Matching Best Generation Algorithm for Partially Shaded Photovoltaic Systems

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Abstract: *This paper proposes a new active electrical reconfiguration algorithm for the partially shaded Photovoltaic array systems. This algorithm can produce higher power compared to other methods which are proposed earlier. In the proposed method, total Photovoltaic array is split into two half, one is the male part and another is the female part. Each part is having equal rows and almost equal columns. The couple matching best generation algorithm is introduced in this paper, which uses short circuit current of each row and switching matrix circuit to extract maximum power. The short circuit current is used to find the weak and healthy rows of both male and female part and switching matrix circuit is used to couple the weaker with the healthier for the best power generation. This reconfiguration is simple, and easy for implementation. The proposed system extract maximum power compared to other existing methods. In this paper the proposed method is discussed with 3×4 array, which can also be extended for any type of array combinations. The simulation of the proposed method is performed in MATLAB software and the results are verified in hardware.*

Key Words: *Photovoltaic, Electrical Reconfiguration, Total Cross Tied, Partial Shading, Maximum Power, Switching Control.*

1. Introduction.

In today's world the increasing energy requirements for about all kinds of industrial and household applications and the disadvantages of the conventional energy sources such as co_2 emission, inadequate amount, etc; have attracted the attention to the renewable energy resources. The photovoltaic power generation system is developing rapidly and showing good industrial growth worldwide. This has resulted in an increased demand for knowledge of PV devices and system performances. Thus solar energy sources have been considered by many researchers. However solar power generation has still some major problems such as low conversion efficiency, high cost and partial shading. In solar power plants, partial shading is one of the biggest challenges. The solar panel's power generation is easily affected by clouds, birds and dust [1] resulting in partial shading in the PV array. This partial shading reduces the other panel's power generation and the resulting impacts are overcome by two methods one is by using Maximum Power Point Tracking (MPPT) method and the another one by using reconfiguration method. During partial shading the P-V characteristic curve of the PV array has multiple peaks and due to this conventional MPPT is not suitable to track the maximum power because the peak power point detected may not be the global maximum power point.

To solve this problem many researchers developed new algorithms and techniques. TCT connection of PV panels is one of the array configuration techniques which are used to obtain a single peak in the P-V characteristic during partial shading condition. The conventional MPPT techniques such as Perturb and Observer (P&O) method and Incremental Conductance (IC) algorithm are enough to detect the maximum power point. But the maximum power obtained may not be the global maximum power because under partial shading condition, the current gets limited in the TCT array. This reduces the maximum power output of the array. The shading pattern and array configuration are the important factors that influence the current limitation. Different array configuration schemes such as Series Parallel (SP), Total Cross Tied (TCT) and Bridge Linked (BL) have been proposed in literature for reducing the current limitation [2]. Researchers have proved that, TCT offers minimum current limitations under partial shading conditions.

In TCT, the maximum shaded panels in a row limits the maximum current output of the array. When the number of shaded panels in a row is decreased by reconfiguration, the maximum current output of the array gets increased. Thereby maximum power output of the array is also increased. A variety of reconfiguration methods are proposed in various literatures to reduce the current limitation during partial shading conditions. The reconfiguration methods are classified into two types one is the static reconfiguration and another one is the dynamic reconfiguration.

In static reconfiguration the physical location of the panels are changed but the electrical connection remains the same. In dynamic reconfiguration electrical connection of the panels are changed but the physical location remains the same. Vaibhav Vaidya and Denise Wilson developed a Time Domain Array Reconfiguration (TDAR) to reduce the current limitation [3]. This method falls under electrical reconfiguration. In this method, the array is reconfigured by switching each panel in and out of the array using duty cycle control. The strongest (high power producing) panels are connected to the array and the weakest (low power producing) are disconnected away from the array. The main drawback is that the obtained power may not be the global maximum power.

Srinivasa Rao Potnuru et al discussed the method to obtain the maximum power even for a large sized array by using optimal Sudoku configuration without modifying TCT base connections [2], and this method falls under static reconfiguration. The physical connections of the panels are optimally reconfigured to reduce the current limitation effect. The length of the conductor is greatly reduced in this method compared to Sudoku. L.Fialho et al discussed about the effects of shading in series solar modules. I-V and P-V characteristics are obtained by parameter identification using heuristic method under normal and partial shading conditions [4]. The shading effects are clearly discussed in this literature. For the partial shaded PV systems, Koray Sener Parlak proposed a reconfiguration method which has fixed and adaptive part along with the switching matrix circuit and this method falls under electrical reconfiguration. This method uses configuration scanning algorithm, which uses short circuit current values of each rows to find the best combination of adaptive and fixed part. Then the adaptive part is connected with the fixed part for the best power generation and this reduces the current limitation of the array [5]. Abdulkader Tabanjat et al proposed a dynamic reconfiguration method to obtain required load output voltage and this method falls under electrical reconfiguration. A switching matrix circuit is used to alter the power flow paths of the PV array and this reduces the current limitation of the array [6]. The existing methods discussed by various researchers are not extracting maximum power from the array. The major drawbacks of the methods discussed in [6] and [5] are that the current limitation not effectively reduced when the number of columns is increased in the array and the computation time for the implementation of the algorithm is also high. To solve the above problem a new algorithm called couple matching best generation algorithm is introduced in this paper.

2. Modeling of PV Panel.

A mathematical model is developed for 10W solar module (Panel) in MATLAB simulink. Figure 1 shows the equivalent circuit of single solar cell using 2 diodes. The I-V characteristic of the solar cell is derived from accurate two exponential diode model [10]. The current output of the solar cell can be derived as

I_L -Light Induced Current

I_0 -Saturation Current of the First Diode

I_{01} -Saturation Current of the Second Diode

k -Boltzmann Constant

T -Device Operating Temperature

q -Elementary Charge on an electron

n_1 -Ideality factor of first Diode (Diode Emission Coefficient)

n_2 -Ideality factor of second Diode (Diode Emission Coefficient)

V -Voltage across the cell

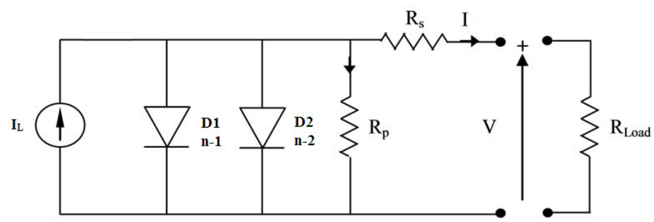

Figure 1. Equivalent circuit of single solar cell using 2 diodes

$$I = I_L - I_0[exp^{\,q(v+IRs)/n_1kT} - 1] - I_{01}[exp^{\,q(v+IRs)/n_2kT} - 1] - \frac{V + IR_s}{R_p} \quad (1)$$

x = Total number of Row in the array

y = Total number of Columns in the array

For using simple MPPT and achieving constant required voltage in PV system, TCT PV array is formed by interconnecting PV panels. Figure 2 shows the existing 3×4 TCT array. For x×y array, 'x' indicates the number of rows and 'y' indicates the number of columns. The strings x_1, x_2, x_3& x_4 indicates the panels in the rows 1, 2, 3 & 4 where as y_1, y_2 & y_3 indicates the panels in the columns 1, 2 &

3 × 4 TCT PV Array

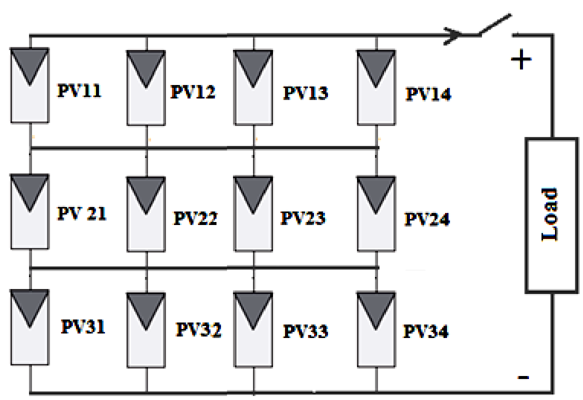

Figure 2. 3×4 TCT Array with 12 Panels

In this paper a 3×4 array (with 12 panels) is implemented for testing the proposed system and it is shown in figure 5.

The ratings of the panel used for MATLAB simulation and hardware implementation are

P_{max} =10W, V_{oc}=21.96V, I_{sc}=0.59A, V_m=18.25, I_m=0.55A.

A 3×4 array is discussed in this paper, the specifications are

P_{max} =120W, V_{oc}=65.88V, I_{sc}=2.36A, V_m=54.75, I_m=2.2A.

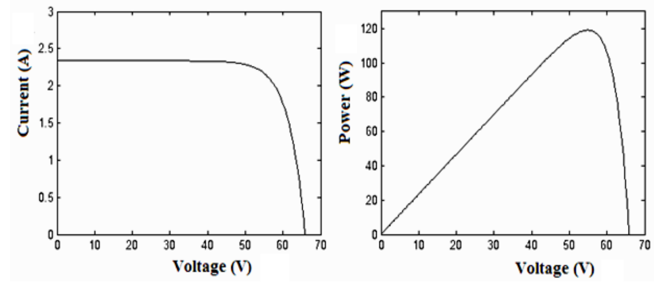

Figure 3. I-V and P-V Curve for the 3×4 TCT array

Array's I-V and P-V characteristics curves obtained in simulation are shown in figure 3. The peak power obtained is 120W at Standard Test Condition (STC) that is under the irradiation of 1000W/m^2 and Temperature of 25^{0}C.

Effect of Partial Shading on the 3 × 4 TCT array

Table 1 shows the obtained simulation result for the 3 × 4 TCT array. From this table it is clear that the row current plays a dominant role in the net load current and also in the net power generation. Partial shading reduces the net power generation by limiting the current flowing through the load. In the table x_1, x_2 and x_3 denotes the row 1, row 2 and row 3 of the array and y_1, y_2 and y_3 denotes the column 1, column 2 and column 3 of the array. The irradiations received by panels are indicated in the corresponding rows and columns. For shading pattern I, all panels are receiving equal irradiation of 1000W/m^2. Here power generated (maximum available power) and delivered to load are equal. In shading pattern II and III, the panels are receiving various irradiations due to partial shading and their corresponding power outputs are reduced compared to the maximum available power. The I_{sc} Row 1, I_{sc} Row 2 and I_{sc} Row 3 indicates the short circuit current of each row in the array. For shading pattern I (uniform shading), there is no change in short circuit current, load side short circuit current, maximum available power and power delivered to load. In case of shading pattern II & III (partial shading), there is a change in short circuit current and load side short circuit current, which implies that the current is limited. Due to this the power delivered to load is low compared to the maximum available power.

3. Conventional Reconfiguration Methods.

The recent reconfiguration methods proposed in the literature are Scanning Algorithm based reconfiguration [2] and Switching Control based reconfiguration [1].

Scanning Algorithm based Reconfiguration

In this method, panels in one column are taken as adaptive part and the remaining as fixed part. The short circuit current of each row in the fixed part and each panel in the adaptive part is measured by switching control. Then the measured current is given to the scanning algorithm. The scanning algorithm calculates the Current Variation Index (CVI) for all possible combinations of the adaptive and fixed part and then it finds the best combination by choosing the minimum CVI combination.

Table 1. Load Current and Power Variation in the 3 × 4 TCT array.

Shading Pattern					I_{sc} Row 1 (A)	I_{sc} Row 2 (A)	I_{sc} Row 3 (A)	Load side Isc (A)	Maximum Available Power (W)	Power Delivered to Load (W)
I	y_1	y_2	y_3	y_4	**2.36**	**2.36**	**2.36**	**2.36**	**120**	**120**
x_1	1000	1000	1000	1000						
x_2	1000	1000	1000	1000						
x_3	1000	1000	1000	1000						
II	y_1	y_2	y_3	y_4	**2.36**	**1.44**	**2.36**	**1.44**	**104.7**	**73.3**
x_1	1000	1000	1000	1000						
x_2	1000	500	500	500						
x_3	1000	1000	1000	1000						
III	y_1	y_2	y_3	y_4	**1.98**	**1.19**	**2.36**	**1.19**	**94.0**	**65.2**
x_1	1000	800	1000	600						
x_2	600	500	500	500						
x_3	1000	1000	1000	1000						

Then for that combination, the adaptive part panels are reconfigured to improve the power output. The main drawbacks of this method are:

1) Panels in the adaptive part are not sufficient to improve the power output when the columns are increased in the array.
2) Computation time for finding the best combinations is high since it checks for all the possible combinations.

For array construction in solar power systems first the rows are fixed by the voltage requirement and then columns are increased (depends on the power requirement). So, columns are increased when the power requirement increases.

In this method, the total array (both adaptive and fixed part) is disconnected away from the load during short circuit current measurement and scanning algorithm implementation. So, the increase in computation time of the algorithm will affect the plant load factor.

Switching Control based Reconfiguration

In this method the panels are grouped in to PV1, PV2, PV3 and PV4. The panels in each group are controlled individually to get a constant output voltage at the load terminal. The panels are connected and disconnected from the group with the help of switches in each panel and also in the array. The fuzzy logic estimator is used to find the minimum and maximum voltage generated by each group and then the switching rules are implemented to control all the switches in the array. Maintaining the constant terminal voltage is the main advantage of this method.

The main drawbacks of this method are:

1) For higher power generation, switches requirement are high since each panels are controlled.

2) The power output may not be the real maximum at partially shading conditions since the panels are disconnected away during partial shading conditions.
3) During partially shading condition, the power output is very low compared to scanning algorithm based reconfiguration.

4. Couple Matching.

Normally couples are matched by considering various criteria. If we require best generation from all the couples in the group of people (having equal young male and female), then the healthier one should be coupled with the weaker one and vice versa. This is called Couple Matching and is shown in figure 4. Depending on the health, males and females are categorized and then coupled to get the best generation. The healthier one gets the first position in both male and female.

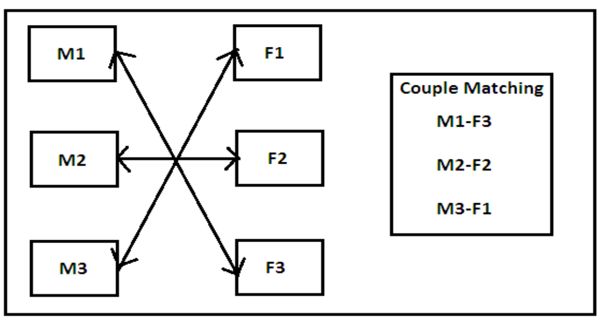

Figure 4. Male and Female Couple Matching

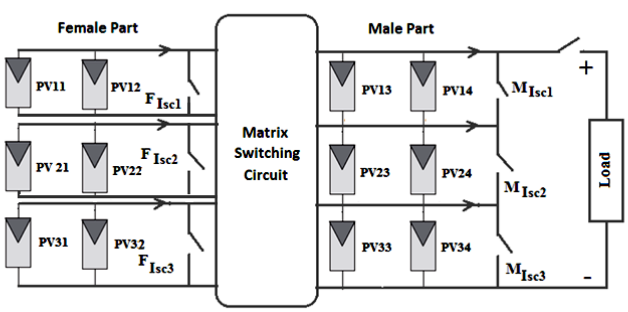

Figure 5. 3×4 Proposed Array with 12 Panels

In the figure 4 M1, M2 and M3 are males and F1, F2 and F3 are females. The health of M1 is good compared to M2 and the health of M2 is good compared to M3. For female the case is same as male. For this group, the couples should be matched as M1-F3, M2-F2 and M3-F1, in order to get best generation. This kind of couple matching results in almost equal health condition in all generation of the couples.

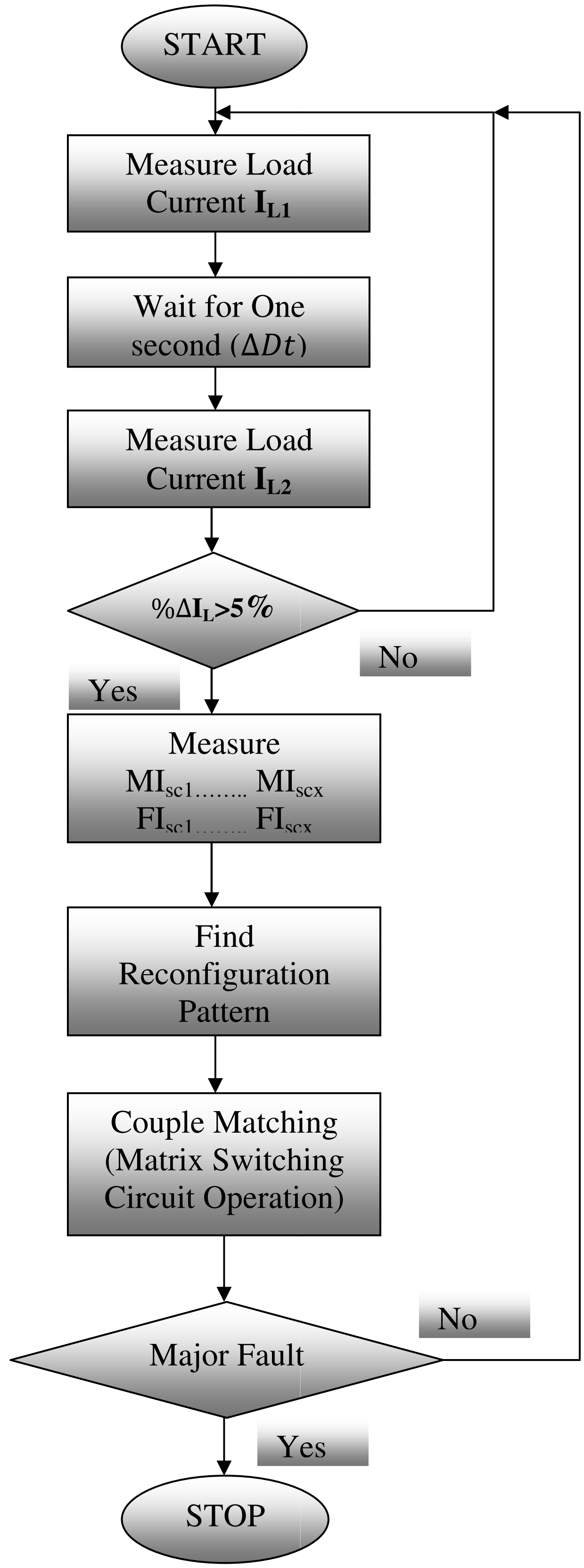

Figure 6. Flow Chart of the Proposed Algorithm

Couple Matching Best Generation Algorithm

M = Each Male Panel's Short Circuit Current

F = Each Female Panel's Short Circuit Current

M_S = Each Male Panel's Short Circuit Current Starting from highest value

F_S = Each Female Panel's Short Circuit Current Starting from highest value

RC = Reconfiguration Pattern

M_{SS} = Position Number of Male Panels

F_{SS} = Position Number of Female Panels

The figure 5 shows the proposed 3×4 TCT array system for implementing Couple Matching Best Generation Algorithm. In conventional TCT PV array, the important constraint is that the entire row's current should be almost equal otherwise power generation will not be maximum. So, the concept of couple matching is used in the PV system to generate maximum power and is called as Couple Matching Best Generation Algorithm. The proposed algorithm overcomes the drawbacks of the conventional methods. In this proposed algorithm total rows and columns of the PV array are almost equally split into two parts one the male part another one the female part. Rows in male and female part decide the total number of males and females.

Equation 2 is used to calculate the total number of columns in the male and female part. If the array's total number of columns is not even in number then the male part has one column higher than the female part and if it is even then both columns are equal.

Male Part Columns = $||\frac{y}{2}||$;

Female Part Columns = Total Columns - $||\frac{y}{2}||$ (2)

Equation 3 is used to calculate the total number of rows in the male and female part. The rows are always equal for both the parts.

Male Part Rows = x ; Female Part Rows = x (3)

The 3 × 4 TCT array can be split into 3 × 2 male part and 3 × 2 female part and so, male part has 3 males and female part has 3 females. Figure 6 shows the flowchart of the proposed method. Initially load current is measured and after five seconds again the load current is measured and then the percentage change in current is calculated by equation 4. Percentage change in load current is represented as (% ΔI_L).

$$\%\ \Delta I_L = \frac{I_{L1} - I_{L2}}{I_{L1}} \times 100 \quad (4)$$

In a day during normal condition, the load current gradually increases in the forenoon and then decreases in the afternoon. During partial shading, the load current suddenly decreases (more than 5% within a fraction of second). This helps to identify the partial shading period. In Couple Matching Best Generation Algorithm, if the first condition is satisfied (if the percentage change in load current exceeds five percent) then panels are reconfigured.

Implementation Results of the Proposed Method in the 3×4 array

Figure 7 shows the MATLAB simulink diagram of the proposed system. Current limitation and power generation of the proposed system is compared with conventional system under various shading patterns. In simulation, partial shading is created by setting various irradiations to the panels males and females. Table 2 shows the various types of shading patterns. In shading type I all the panels are receiving equal irradiations, in the remaining types the irradiation are not equal. The panel's irradiation corresponding to the rows and columns are given in W/m^2. Table 3 shows the current limitation results of the proposed system before and after reconfiguration under various shading patterns. Individual males and females short circuit current is also given. From the table it is clear that the proposed Couple Matching Best Generation Algorithm results in reduced current limitation compared to the existing. Table 4 shows the comparison of conventional and proposed system reconfiguration methods. From that also it is clear that the proposed method needs same number of switches for the reconfiguration but it leads to reduction in computation time, reduction in current limitation and increase in power generation. In the Scanning Algorithm based reconfiguration Current Variation Index (CVI) is calculated. Calculating CVI needs high computation time because all the possible combinations of fixed and adaptive part should be checked.

Practical Implementation

The picture shown in figure 9 shows the practical experimental setup of the proposed system. Twelve panels are used for constructing the array. For the reconfiguration, Normally Opened and Normally Closed (NONC) relays are used for the construction of matrix circuit. For controlling the relays, transistor (BC547) based driver circuits are used. For finding the short circuit and load current, current sensor ACS712 modules are used. Arduino mega2560 (micro controller) is used for implementing the proposed Couple Matching Best Generation Algorithm. For creating partial shading, panels are hidden by using cardboard sheet. For obtaining the irradiation values in W/m^2, Luminance (lx) value of the sunlight reaching the panel is substituted in the equation 5. It will give irradiation in W/m^2. The Luminous Efficacy of the sunlight is 93lm/W. Table 5 shows the comparison of the proposed with other results. Both simulation and experimental results shows that proposed system extracts maximum power during partial shading conditions.

E_v= Luminance in Lux (lx)

A = Area in m^2

η = Luminous Efficacy in Lumens (lm)/Watts (W)

$$\text{Irradiation } (P_{ir}) = E_v \times A \times \eta \quad (5)$$

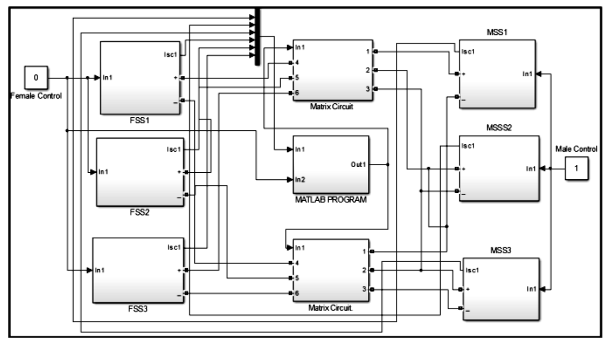

Figure 7. MATLAB Simulink Diagram of the Proposed System

Table 2. Various Shading Patterns for testing the Proposed System.

Shading Pattern for Male and Female Part								**Shading Type**
Female		**y_1**	**y_2**	**Male**		**y_3**	**y_4**	**I**
FS_{11}	**x_1**	**1000**	**1000**	**MS_{11}**	**x_1**	**1000**	**1000**	
FS_{22}	**x_2**	**1000**	**1000**	**MS_{22}**	**x_2**	**1000**	**1000**	
FS_{33}	**x_3**	**1000**	**1000**	**MS_{33}**	**x_3**	**1000**	**1000**	
Female		**y_1**	**y_2**	**Male**		**y_3**	**y_4**	**II**
FS_{11}	**x_1**	**200**	**400**	**MS_{11}**	**x_1**	**200**	**200**	
FS_{22}	**x_2**	**200**	**500**	**MS_{22}**	**x_2**	**1000**	**1000**	
FS_{33}	**x_3**	**1000**	**1000**	**MS_{33}**	**x_3**	**1000**	**1000**	
Female		**y_1**	**y_2**	**Male**		**y_3**	**y_4**	**III**
FS_{11}	**x_1**	**200**	**100**	**MS_{11}**	**x_1**	**1000**	**1000**	
FS_{22}	**x_2**	**500**	**500**	**MS_{22}**	**x_2**	**500**	**500**	
FS_{33}	**x_3**	**300**	**300**	**MS_{33}**	**x_3**	**300**	**400**	
Female		**y_1**	**y_2**	**Male**		**y_3**	**y_4**	**IV**
FS_{11}	**x_1**	**600**	**1000**	**MS_{11}**	**x_1**	**1000**	**1000**	
FS_{22}	**x_2**	**500**	**500**	**MS_{22}**	**x_2**	**200**	**200**	
FS_{33}	**x_3**	**300**	**300**	**MS_{33}**	**x_3**	**300**	**400**	
Female		**y_1**	**y_2**	**Male**		**y_3**	**y_4**	**V**
FS_{11}	**x_1**	**300**	**1000**	**MS_{11}**	**x_1**	**500**	**500**	
FS_{22}	**x_2**	**300**	**500**	**MS_{22}**	**x_2**	**200**	**200**	
FS_{33}	**x_3**	**300**	**300**	**MS_{33}**	**x_3**	**300**	**400**	

Table 3. Results of the Proposed System under various shading patterns.

Shading Type	Short Circuit Current (A)						Before Reconfiguration Load Side I_{sc} (A)	After Reconfiguration Load Side I_{sc} (A)
	Male			Female				
	M1	M2	M3	F1	F2	F3		
I	1.18	1.18	1.18	1.18	1.18	1.18	2.36	2.36
II	0.22	1.18	1.18	0.34	0.39	1.18	0.56	1.4
III	1.18	0.57	0.39	0.70	0.57	0.34	0.73	1.09
IV	1.18	0.22	0.39	0.93	0.57	0.34	0.73	0.96
V	0.57	0.22	0.39	0.76	0.45	0.34	0.67	0.84

Table 4. Comparison of Reconfiguration Methods.

Type	Scanning Algorithm based Reconfiguration	Couple Matching Best Generation Algorithm
Switch Requirement 3×4 Array	25	25
Computation Time (Software: MATLAB R2013a Processor: Core i3-3110M CPU:2.40GHz, RAM:4GB, System Type:32 bit)	High (2.1ms)	Low (0.04ms)
Current Limitation Reduction	Low	High
Power Generation	Low	High

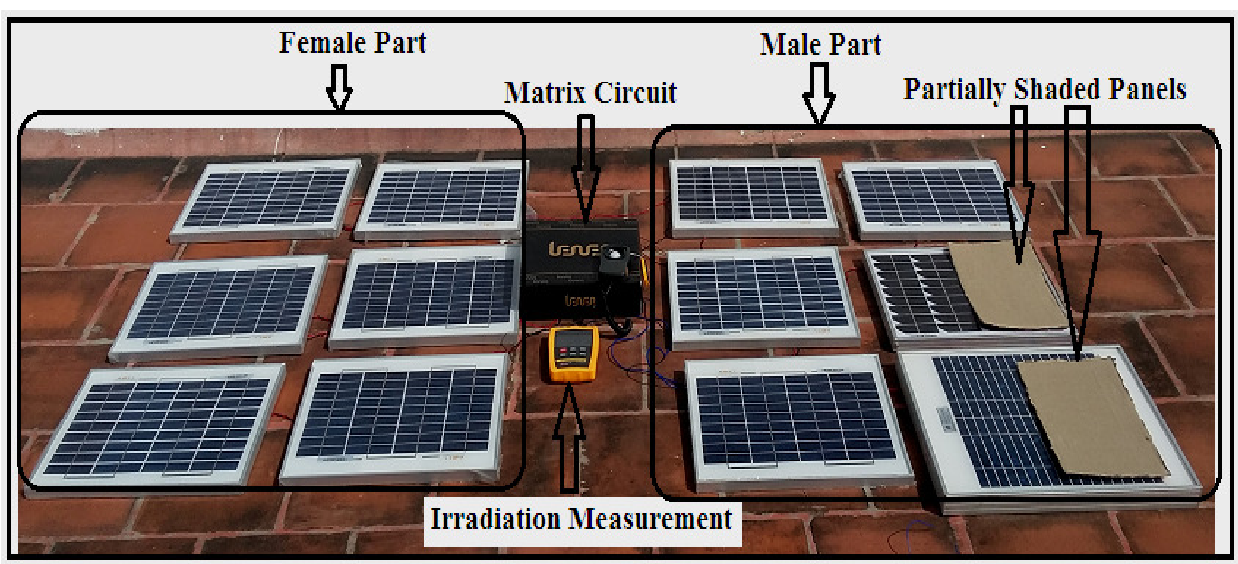

Figure 9. Practical Experimental Setup of the Proposed System

Table 5. Power Generation Comparison for various Reconfiguration Methods.

Shading Type	Normal TCT Array		Scanning Algorithm based Reconfiguration		Proposed Reconfiguration	
	Simulation (W)	Practical (W)	Simulation (W)	Practical (W)	Simulation (W)	Practical (W)
I	120	118.5	120	118.5	120	118.5
II	28.5	28.0	64.3	63.0	71.4	70.5
III	37.3	36.5	50.0	49.5	55.6	54.5
IV	37.3	36.5	43.4	42.5	50.0	49.0
V	34.2	33.0	37.2	36.0	42.9	41.5

5. Conclusion.

In this paper, a new reconfiguration algorithm called Couple Matching Best Generation Algorithm has been proposed in order to reduce the current limitation of the TCT array. The proposed method extracts maximum power from a 3×4 PV array under partial shading conditions. The obtained results show that the proposed method extracts the maximum power compared to the other existing methods. In this proposed method, total panels in the array are grouped into male and female parts. Male part is coupled with the female part for the best power generation of the PV array. The best power generation is achieved by matching the stronger one with the weaker one. The proposed algorithm is implemented in both simulation and practical setup for the 3×4 PV array. In simulation, partial shading is created by varying the irradiation of the panels in the array. In practical setup, partial shading is created by hiding the panels in the array by cardboard sheet. The obtained practical results are on par with the simulation results. Both the simulation and practical results shows that the current limitation has been decreased in the proposed method during partial shading conditions. The main advantages of this method are additional switches are not required, computation time is very low, current limitation is greatly reduced and power generation is improved.

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