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Solar PV array reconfiguration under partial shading conditions for maximum power extraction using genetic algorithm

Shubhankar Niranjan Deshkar, Sumedh Bhaskar Dhale, Jishnu Shekar Mukherjee, T. Sudhakar Babu*, N. Rajasekar

School of Electrical Engineering, VIT University, Vellore 632014, Tamilnadu, India

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ABSTRACT

The contribution of renewable energy to the field of energy markets has been substantial over the last few years. A large number of PV array installations show the increasing contribution of solar energy to the renewable energy. Partial shading of the PV arrays is one of the most discussed and worked upon concept for the simple reasons that it decreases the power output of the PV array installations and exhibits multiple peaks in the *I–V* characteristics. As a result, the modules have to be reconfigured to get the maximum power output. This papers presents an optimization based approach for Total cross tied (TCT) connected modules in a PV array. The physical locations of the modules remain unchanged while the electrical connections are altered. The genetic algorithm (GA) as an optimization tool, gives the connection matrix for the new electrical interconnection which fetches the maximum power output from the PV array. This is done to obtain uniform dispersion of shadow throughout the panel.

Contents

1. Introduction

The nonrenewable energy resources have started exhausting at an alarming rate and the world today has entered into energy crisis. As a consequence, increasing use of the renewable energy resources like the solar, wind, tidal etc., is the most evident solution to alleviate this problem [1,2]. There has been a lot of improvisation in the power semiconductor technology over the years. As a consequence the cost of the photovoltaic cells has reduced to a great extent which makes solar energy one of the most sought after solutions. Moreover, the added advantage is that the sunlight is available at free of cost and its use does not pollute the environment [3,4]. The total solar energy installed capacity as on December 2013 is 2180 MW and has got a potential to contribute 12,500 MW to the power demand of India till 2016–2017 [5]. This is equivalent to saving 61 MT of coal per annum.

The efficiency of a single solar PV module is very less and remains a matter of concern. Furthermore, a single module is incapable of catering to large load requirements. Therefore, interconnection is recommended to meet higher load demands.

* Corresponding author. Tel.: +91 9600117935.
E-mail address: sudhakar.babu2013@vit.ac.in (T.S. Babu).

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The modules may be connected in series or parallel. The series interconnection scheme offers a higher output voltage which is the voltage sum of the individual array voltage. Consequently, current is limited to individual module current due to series connection. The power generated in this case is no doubt more than a single module, but it can only cater to medium power loads. Same is the case with parallel connection wherein, the system current is the current sum of individual module currents and system voltage is limited to the voltage of an individual module. Therefore, to cater to the high power loads a variety of interconnection patterns like Series–parallel (SP) (combination of series and parallel connection scheme), Bridge linked (BL), Total Cross Tied (TCT) and Honey Comb (HC) are proposed [6,7] for the solar PV modules. Series–parallel connections are the most common configurations and are generally used to meet the load power requirements. However, if some panels in the array are subjected to shading, the output power may decrease substantially. Big trees, hoardings, poles, towers etc. can be the causes of the partial shading [8,9]. Thus, partial shading unevenly distributes the shadow on the solar PV array. Thus, in addition to decreased power yield from the array, the PV and IV characteristics are also disturbed by partial shading. Multiple peaks in the PV characteristics and steps in the IV characteristics are the perturbing effects of partial shading [10,11].

Apart from maximum power, parameters like life of the array, mismatch losses and reliability playing an equally crucial role in deciding the performance of the array. As reported [12] introducing cross ties may enhance the life of an array. Results shown in [13] prove that the TCT arrangement is the best solution to accentuate the problem of mismatch losses under partial shading. This conclusion was however pinned down by the results presented by Su Do Ku rearrangement scheme [14]. This reconfiguration technique gives smooth and steadily increasing PV characteristics as compared to the TCT configuration. The Su Do Ku technique gives higher maximum power output and the problem of multiple peaks suffered by the TCT arrangement is also dealt. However, physical relocation proposed by this scheme is not recommended as it involves physical labor, excessive length of the interconnecting wires leading to increased losses. Moreover managing the interconnecting ties having excessive length for 81 PV modules is a tedious job. Also, the wires can be easily tampered and replacing these copper wires every time may prove to be expensive.

Considering the above facts, this paper proposes a unique method for array reconfiguration using genetic algorithm (GA) based approach. The proposed GA aims at equalizing the individual row currents and at the same time maximize the power output. In the proposed method, the physical locations of the modules remain the same. The electrical interconnections however change, thus giving the effect of uniform shadow dispersion. The real time implementation for this scheme can be achieved using the electronic controllers, current sensors and switching networks. The proposed optimization technique is implemented on a 9×9 PV array to get the interconnection matrix. Thus, given an irradiation pattern for the array, the algorithm finds out the best possible interconnection which gives the maximum output power for the shading pattern specified. Different shading patterns are used to test the performance of the system under consideration.

In addition, the performance analysis shows that the GA based approach yields enhanced power output as compared to the Su Do Ku scheme. Also, the I–V characteristics obtained are presented later in Section 4 which shows that the proposed method gives next to ideal (no steps) characteristics. This in turn reduces the mismatch losses and the probability of panels getting bypassed is drastically reduced giving increased power output. This implies that the shade dispersion provided by this method is better as compared to the Su Do Ku pattern.

2. System description

2.1. Model of a solar (PV) cell

Fig. 1 shows the equivalent circuit of a practical PV cell where the generated current *Iph* is proportional to the irradiation. The recombination losses are represented by the diode connected in parallel to the current source in reverse direction. This is because the recombination current flows in the opposite direction to the light generated current. The I–V equation of a simple solar model can be given by the following expression:

$$I_m = I_{ph} - I_d\left[\exp\left(\frac{q(V_{pv}+I_m R_s)}{nkT}\right)-1\right]-\left(\frac{V_{pv}+I_m R_s}{R_{sh}}\right) \tag{1}$$

where q is the charge on electron, n is the number of cells in series, k is the Boltzmann constant and T is the absolute temperature (Kelvin), I_{ph} is the photoelectric current, I_m is the current generated by the module.

A number of PV cells connected in series constitute a PV module. Typically a module contains 36 PV cells connected in series. The resistance offered by the solar cells in the path of the current flow is denoted by R_s. Resistance offered to the leakage current is represented by R_{sh}. The photoelectric current is a function of the short circuit current and can be expressed as

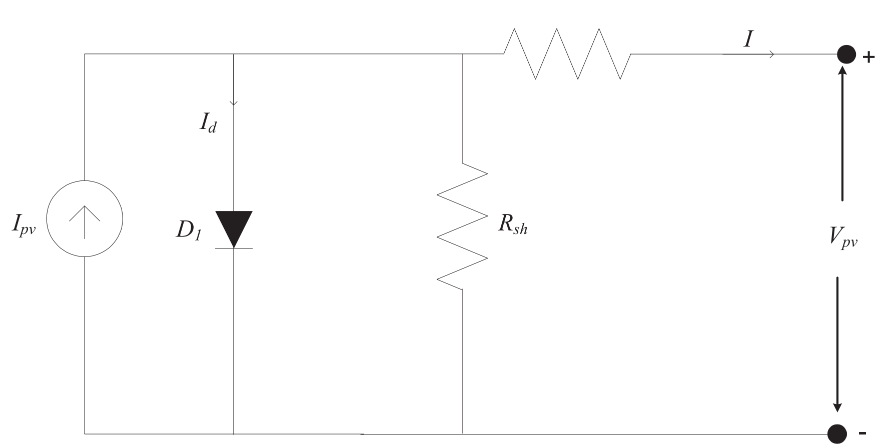

Fig. 1. Equivalent circuit: practical PV cell.

follows

$$I_{ph} = I_{sco}\left(\frac{G}{G_0}\right)(1+\alpha(T-T_o))\left(\frac{R_s+R_{sh}}{R_{sh}}\right) \quad (2)$$

where I_{sco} is the short circuit current of the module at standard insolation G_o (1000 W/m²) and standard temperature T_o (25 °C) and α is the module's temperature coefficient for the current. The PV modules are modeled using the equations mentioned above. The PV module specifications at standard test conditions are mentioned in Table 1.

2.2. TCT configured PV array

The TCT configuration is obtained by connecting cross ties across each row in a simple series parallel (SP) configuration. Fig. 2 shows 9×9 PV array connected in TCT configuration. In other words, the modules in a row are connected in parallel and those in a column are connected in series. The array consists of nine rows and nine columns and a total of 81 PV modules. Suitable labeling is done to identify the individual module. The modules are labeled with subscript '*ij*' where '*i*' denotes the row and '*j*' represents the column in which the module is connected. For instance, if a module has a label '84', then it is located in the eighth row and fourth column. Due to the additional interconnections among the modules in TCT arrangement, the numbers of loops created are more, which consequently increases the redundancy of the array circuit. As a result, even after abiding by the voltage constraints in the circuit, different values of current can flow through the strings of the PV module connected in the same string. Thus, the current generated by the module at an irradiance G is given by

$$I = kI_m \quad (3)$$

where I_m is the current generated by the module at standard irradiance G_0 (1000 W/m²) and $k = G/G_0$. The Kirchhoff's laws are powerful tools to calculate the system voltages and currents. Therefore, by applying KVL, we can find the array voltage which is the sum of the voltages of the nine rows

$$V_a = \sum_{i=1}^{9} V_{mi} \quad (4)$$

where V_a represents the voltage of the PV array and V_{mi} is the voltage of the panels at the *i*th row. The current at each node in the array can be calculated using the Kirchhoff's current law.

$$I_a = \sum_{j=1}^{9} \left(I_{ij} - I_{(i+1)j}\right) = 0, i = 1, 2, 3, \ldots, 8 \quad (5)$$

Table 1
Specifications for PV at 1000 w/m² and 25 °C.

PV power	80 W
Open circuit voltage	21.24 V
Short circuit current	4.74 A
Nominal voltage	17.64 V
Nominal current	4.54 A

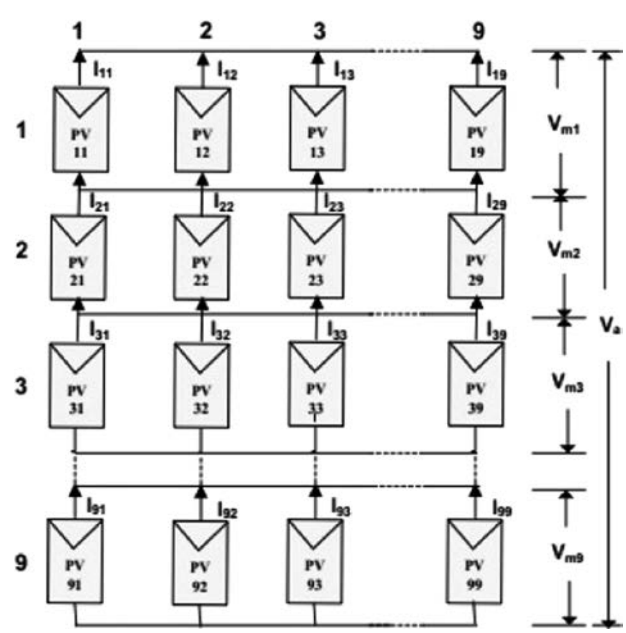

Fig. 2. PV array connected in TCT configuration.

2.3. Su Do Ku configured PV array

In spite of rendering superior performance as compared to the conventional interconnection schemes, the TCT configuration suffers from some drawbacks. The electrical interconnections in the array are intact and so are the physical locations. As a result, this scheme is unable to disperse the shadow uniformly all over the array. Consequently, the row currents being a function of insolation levels also vary over a wide range. Therefore, the panels with lower value of row currents are bypassed to protect them from getting damaged. However, bypassing leads to the stepped *I–V* characteristics and increased mismatch losses. This problem is dealt by the Su Do Ku puzzle arrangement [6] by physically reconfiguring the panels in the array to avoid bypassing and consequently avoid the related undesired consequences.

The reconfiguration is done by physically displacing the panels from their original location to a new location in any row, but within the same column provided by the solution of the puzzle. The physical relocation is done by keeping the electrical connections intact and hence the equations for TCT arrangement are also valid for the Su Do Ku pattern. The Su Do Ku arrangement disperses the concentrated shadow uniformly over the entire panel so as to minimize the bypassing of the panels. This method also facilitates an increase in the node current under the partial shading condition. Thus for the same shading pattern, the power generated using Su Do Ku arrangement is higher than that generated using the TCT arrangement.

However, the Su Do Ku arrangement has many drawbacks. First, it involves laborious task of physical relocation. Second, though the difference in row currents is less for different array voltages as compared to the TCT scheme, it is not minimum and shows a scope of improvement. This implies that the mismatch losses can still be reduced to give enhanced power output. Hence, to overcome these drawbacks, GA based array reconfiguration technique is proposed in the following section.

3. Proposed GA based technique

To approach the given problem of array reconfiguration under partial shading, genetic algorithm (GA) based optimization technique is proposed. It is based on Darwin's principle of "survival of fittest". This method is chosen for the given problem as it can be implemented with real time coding. This allows tracking of individual element during successive iterations. Another advantage is that, the objective function formulation becomes very simple. By careful application of weights to the parameters, their relative effect on the convergence can be examined.

The proposed GA based optimization technique focuses on maximization of output power of a solar array connected in TCT formation for different partial shading conditions. The success of GA to any optimization problem largely depends on two major factors:

(i) Population generation.
(ii) Fitness function design.

For the above problem of array reconfiguration, the objective function is defined as follows:

$$Maximize(Fitness(i)) = Sum(P) + \left(\frac{W_e}{E_e}\right) + (W_p * P_a) \quad (6)$$

where

(i) Fitness (i)=Fitness of ith element in the current population.

(ii) Sum $(P) = \sum_{k=1}^{9} I_k \times V_k$

where, V_k and I_k are voltage across the array for current limit of kth row and the current limit, respectively.

(iii) $E_e = \sum_{k=1}^{9} |I_m - I_k|$

where I_m is the maximum possible value of current when bypassing is considered. Here maximum value is taken instead of average to speed up the convergence.

(iv) P_a=Panel output power (without bypassing).

(v) W_e and W_p are the weights assumed for E_e and P_a.

Parameter selection is a major issue in the application of GA, as it directly affects the convergence rate about global optimum. The genetic algorithm method has the tendency of converging at local optimum. However, this phenomenon cannot be removed completely, but can be reduced to a great extent by assigning limits to the parameters. In this work, the parameter limits are assigned purely by trial and error method. It is observed that fixing all the parameters to some specific values mostly results in convergence about local optimum point. Therefore, to make the algorithm converge at the global optimum point, some parameters should be assigned specific values and the other parameters should be provided with some mobility so that they can vary randomly. This work proposes to fix the value of population size and number of iterations to 100 and 800, respectively, whereas the probability of mutation, probability of crossover and point of crossover are allowed to be chosen randomly. It is advised to run the code several times to ensure the convergence at the global optimum. It is observed that, with due consideration of all the above factors, the GA code for the given problem converges at the global optimum almost 7 times in 10 trials. The rate of convergence of the algorithm depends upon ability of the fitness function to decide the best elements among the given population.

4. Results and discussion

To evaluate the performance of the GA based reconfiguration scheme, three types of shading patterns namely (1) short and wide (2) long and narrow (3) short and narrow are considered. The performance of the proposed method is evaluated with the help of a 9 × 9 PV array connected in TCT configuration. The theoretical predictions are verified using simulation in MATLAB/Simulink environment. Simulation is carried for Kotak PV 80 W panel. The results obtained are compared with TCT and Su Do Ku reconfiguration schemes for three types of shading patterns. Further discussion focuses on factors responsible for output power rise in GA reconfigured patterns. Further, to support the validation of the proposed method, the *P–V* curve and *I–V* curve are considered for all the three reconfiguration schemes and discussion is provided based on the result obtained.

The 9 × 9 PV array is subjected to three different shading patterns and in each case the PV array is reconfigured to extract the maximum possible power. In all the three cases the performance of the GA reconfigured PV array is compared with an existing method like the Su Do Ku and TCT configured array.

Case 1. Short and wide shadow.

In this pattern, the PV array is shaded only on one half of the array and it spreads with varying insolation levels. The PV array is subjected to four different insolation's. The first group receives an irradiance of 900 W/m². Second group receives 600 W/m². The third and fourth group receives 400 W/m² and 200 W/m², respectively. Figure shows the irradiation pattern corresponding to Case 1. As mentioned earlier, the row currents are to be calculated to find the location of the GP. It is evident from Fig. 2 that the panels in a row are connected in parallel. Hence maximum possible current output of a row is equal to the sum of the current limits of individual panels. Thus the current limit of the first row is calculated as:

$$I_{R1} = k_{11}I_{11} + k_{12}I_{12} + k_{13}I_{13} + k_{14}I_{14} + k_{15}I_{15} + k_{16}I_{16} + k_{17}I_{17} + k_{18}I_{18} \quad (7)$$

where $k_{1j} = (G_{1j}/G_0)$(j=column index) where G_{1j} is the irradiance and I_{1j} is the current limit for full irradiance ($G_{1j} = G_0$) of the panel labeled 1j. Let I_m be the current limit of the panel for full irradiance ($k_{ij} = 1$) under standard temperature conditions. It is a fair assumption to consider that all the panels are identical. Hence we can assume, $I_{11} = I_{12} = I_{13} = \cdots = I_{19} = I_m$

For the shading pattern shown in Fig. 3(a) the panels in the rows 1 to 5 receive same insolation (900 W/m²). Hence the current limit of the first five rows is calculated as:-

$$I_{R1} = 9 \times 0.9I_m = 8.1I_m \quad (8)$$

$$I_{R1} = I_{R2} = I_{R3} = I_{R4} = I_{R5} \quad (9)$$

where $k_{1j} = 900/1000 = 0.9$

In row 6, the first six panels are subjected to 600 W/m² and the next four panels are subjected to 900 W/m^2. The currents generated by other rows can be expressed in a similar way as given in Eq. (7). Hence the current contributed by row 6 and subsequent rows are:

$$I_{R6} = 5 \times 0.6I_m + 4 \times 0.9I_m = 6.6I_m$$
$$I_{R7} = I_{R8} = I_{R9} = 3 \times 0.6I_m + 3 \times 0.4I_m + 3 \times 0.2I_m = 3.6I_m \quad (10)$$

The current limits of rows vary in accordance with the irradiation they receive. All the row currents are considered in the order in which the panels are bypassed and are specified in Table 2. The full array voltage is given by $V_a = 9V_m$. As the power requirement increases, the rows with lowest current limits is bypassed. For instance if any one row in 9 rows is bypassed then the array voltage drops to

$$V_a = 8V_m + V_d.$$

Since $V_d \ll V_m$, We can assume $V_a = 8V_m$.

If an ideal *I–V* curve is assumed, the array power output with no partial shading is given by

$$P_a = V_a I_m = (9V_m)I_m \quad (11)$$

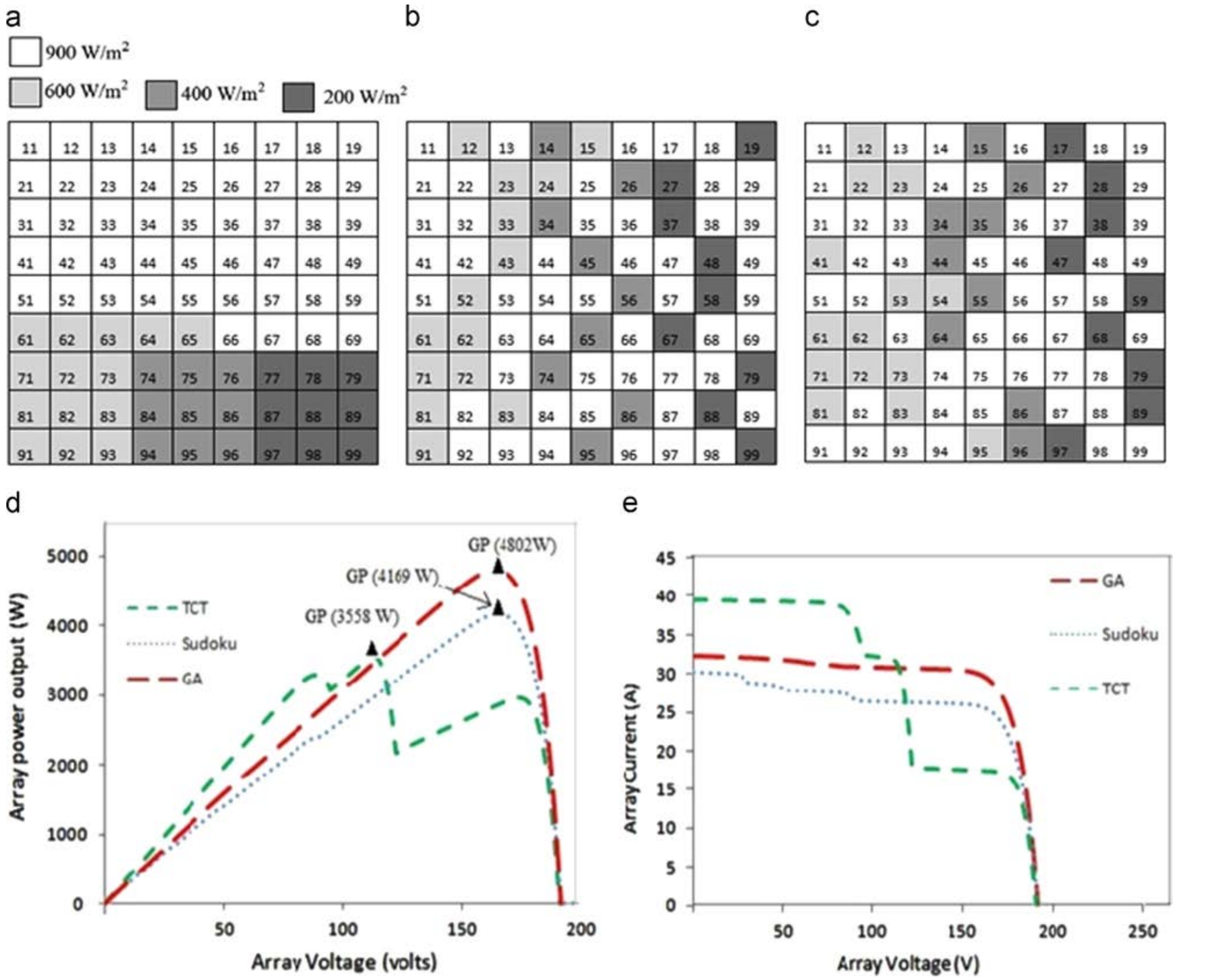

Fig. 3. Shading pattern for case1 (a) TCT interconnection scheme (b) Shade dispersion using Su Do Ku pattern (c) shade dispersion with GA arrangement (d) PV characteristics for TCT, Su Do Ku and GA arrangement (e) IV characteristics for TCT, Su Do Ku and GA arrangement.

Table 2
Location of GP in TCT, SU DO KU and GA arrangement for Case 1.

TCT arrangement				SU DO KU arrangement				GA arrangement			
Row currents in order in which panels are bypassed		Voltage V_A	Power P_A	Row currents in order in which panels are bypassed		Voltage V_A	Power P_A	Row currents in order in which panels are bypassed		Voltage V_A	Power P_A
I_{R9}	$3.6I_m$	$9V_m$	$32.4V_mI_m$	I_{R6}	$6.3I_m$	$9\mathrm{V_m}$	$56.7V_mI_m$	I_{R2}	$6.3I_m$	$9V_m$	$56.7V_mI_m$
I_{R8}	$3.6I_m$	–	–	I_{R7}	$6.3I_m$	–	–	I_{R5}	$6.3I_m$	–	–
I_{R7}	$3.6I_m$	–	–	I_{R8}	$6.3\mathrm{I_m}$	–	–	I_{R6}	$6.3I_m$	–	–
I_{R6}	$6.6I_m$	$6V_m$	$39.6V_mI_m$	I_{R1}	$6.3I_m$	–	–	I_{R8}	$6.3I_m$	–	–
I_{R5}	$8.1I_m$	$5V_m$	$40.5V_mI_m$	I_{R2}	$6.3I_m$	$4V_m$	$26.4V_mI_m$	I_{R3}	$6.4I_m$	$5V_m$	$32V_mI_m$
I_{R4}	$8.1I_m$	–	–	I_{R4}	$6.6I_m$	–	–	I_{R7}	$6.5I_m$	$4V_m$	$26V_mI_m$
I_{R2}	$8.1I_m$	–	–	I_{R3}	$6.6I_m$	–	–	I_{R1}	$6.6I_m$	$3V_m$	$19.8V_mI_m$
$\mathrm{I_{R3}}$	$8.1I_m$	–	–	I_{R5}	$6.6I_m$	–	–	I_{R4}	$6.6I_m$	–	–
I_{R1}	$8.1I_m$	–	–	I_{R9}	$6.6I_m$	–	–	I_{R9}	$6.6I_m$	–	–

Eq. (11) is valid only when no row is bypassed. Considering the order of bypassing, the respective voltages of the arrays and the corresponding powers are calculated as shown in Table 2.

The simulated PV curve for TCT pattern shows that the location of the GP is far away from the nominal voltage of the array. This is because the maximum power is extracted only when rows 6, 7, 8 and 9 are bypassed. As the rows are bypassed, the array voltage drops down to 5 V m at which maximum power is extracted. Further, it can be seen that the PV array generates a maximum of 3558 W and the GP occurs at 112.56 V. This voltage is very much less than the nominal voltage of the array.

With the Su Do Ku configuration the PV array is subjected to shade dispersion. The individual row current limits and the respective powers for the same after bypassing are summed up concisely in Table 2. It is very much evident from the simulation results that the array voltage is improved and it is nearer to the nominal voltage of the array after reconfiguration. Furthermore, the power output for Su Do Ku arrangement is 4169 W which is higher than that obtained in TCT arrangement.

The validation of the proposed GA based method is done using the same PV array which is subjected to the same shading pattern. Reconfiguration using the proposed technique is done to uniformly distribute the effect of shading over the entire panel. Any module in a column may be replaced by any other module from the same column and this constraint is taken care of during problem formulation. Thus, the current in each row is given by

$$
\begin{aligned}
&I_{R1} = I_{R4} = I_{R9} = 6 \times 0.9I_m + 2 \times 0.4I_m + 0.2I_m = 6.6I_m \\
&I_{R7} = 5 \times 0.9I_m + 3 \times 0.6I_m + 0.2I_m = 6.5I_m \\
&I_{R3} = 6 \times 0.9I_m + 2 \times 0.4I_m + 0.2I_m = 6.4I_m \\
&I_{R2} = I_{R5} = I_{R6} = I_{R8} = 5 \times 0.9I_m + 2 \times 0.6I_m + 0.4I_m + 0.2I_m = 6.3I_m
\end{aligned} \tag{12}
$$

Table 2 shows the module currents and the voltages as per the order in which panels are bypassed. Also from the entries in Table 2, it is evident that after rearrangement using GA approach, the GP occurs at a voltage very near to the nominal array voltage. Furthermore, the output power of the array is increased from 4169 W to 4802 as compared to the Su Do Ku pattern. As compared to the TCT arrangement, the output power increases from 3558 W to 4802 W (Fig. 3(d)).

Another important point to be noted from Table2 is that the maximum coefficient of power for Su Do Ku configuration and the GA based approach are same, but the that maximum power is more for GA based approach as compared to Su Do Ku arrangement. The reason behind this can be analyzed with the help of *I–V* characteristics shown in Fig. 3(e). Before analyzing, some points should be noted such as at any instant of time current flowing through the entire array is same and as the current requirement by the load increases, rows incapable of handling higher values of current are bypassed which prevents them from getting damaged. This causes the voltage to drop down to lower level which is clearly evident from Table 2. Starting with the analysis, it should be understood that the current and the voltage coefficients expressed in row one of Table 2 are the maximum limits when no panels are bypassed for both Su Do Ku and GA arrangement. The reason behind the difference in maximum power that can be extracted from Su Do Ku and GA arrangement is due to the nature of *I–V* curves. From Fig. 3(e) it can be seen that droop in *I–V* characteristics is more evident in case of Su Do Ku arrangement than that of GA arrangement. In other words it can be said that for higher values of current the voltage remains considerably higher for GA arrangement due to which we get higher value of power for that condition. The Sum (P) component considered in the fitness function design is the main reason due to which the *I–V* characteristics are better for GA arrangement.

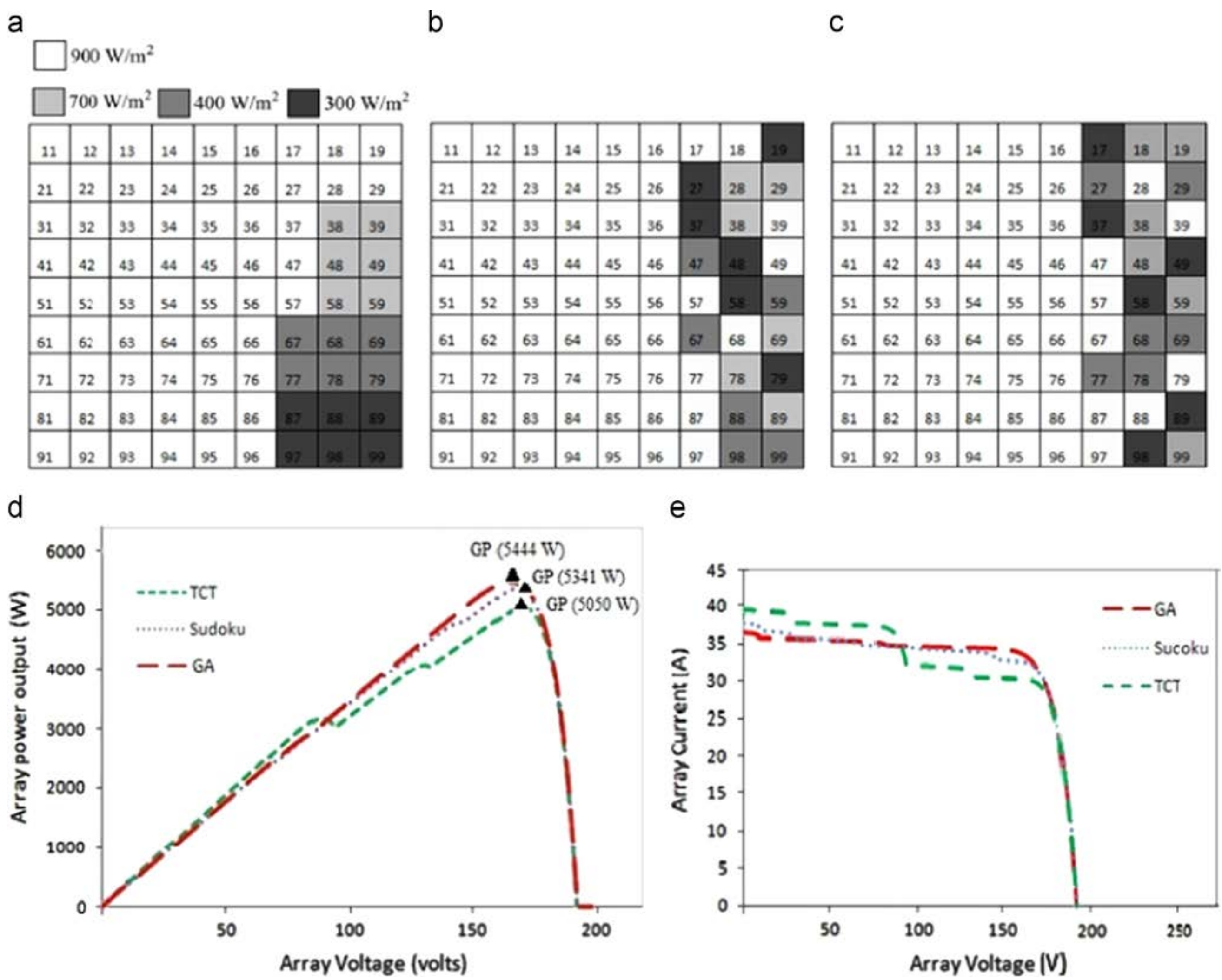

Fig. 4. Shading pattern for case2 (a) TCT interconnection scheme (b) shade dispersion using Su Do Ku pattern (c) shade dispersion with GA arrangement (d) PV characteristics for TCT, Su Do Ku and GA arrangement (e) IV characteristics for TCT, Su Do Ku and GA arrangement.

As evident from Fig. 3(e), with GA based approach, as the current drawn increases, the drop in the array voltage is less as compared to the Su Do Ku and TCT arrangement. Moreover, the current supplied at a specific voltage is also more for the proposed approach as compared to the Su Do Ku pattern. This is the reason why enhanced power output is obtained in spite of same limiting coefficients. Thus, in a way, the *I*–*V* characteristics prove to be a supporting evidence for the increase in the array output power by minimizing the mismatch losses. The importance of equalizing the row currents and increasing the minimum current is discussed in [14–16].

Case 2. Long and narrow shadow.

This case is so called as only a few of the columns are subjected to partial shading and may appear anywhere in the array in the form of a group. From Fig. 4(a) it can be seen that the array in this case experiences four irradiation levels which are 900 W/m^2,

Table 3
Location of GP in TCT, SU Do KU and GA arrangement for Case 2.

TCT arrangement				SU DO KU arrangement				GA arrangement			
Row currents in order in which panels are bypassed		Voltage V_A	Power P_A	Row currents in order in which panels are bypassed		Voltage V_A	Power P_A	Row currents in order in which panels are bypassed		Voltage V_A	Power P_A
I_{R8}	$6.3I_m$	$9V_m$	$56.7V_mI_m$	I_{R4}	$7.0I_m$	$9V_m$	$63.0V_mI_m$	I_{R1}	$7.1I_m$	$9V_m$	$63.9V_mI_m$
I_{R9}	$6.3I_m$	–	–	I_{R5}	$7.0I_m$	–	–	I_{R2}	$7.1I_m$	–	–
I_{R6}	$6.6I_m$	$7V_m$	$46.2V_mI_m$	I_{R2}	$7.1I_m$	$7V_m$	$49.7V_mI_m$	I_{R6}	$7.1I_m$	–	–
I_{R7}	$6.6I_m$	–	–	I_{R9}	$7.1I_m$	–	–	I_{R7}	$7.1I_m$	–	–
I_{R3}	$7.7I_m$	$5V_m$	$38.5V_mI_m$	I_{R3}	$7.3I_m$	$5V_m$	$36.5V_mI_m$	I_{R3}	$7.3I_m$	$5V_m$	$36.5V_mI_m$
I_{R4}	$7.7I_m$	–	–	I_{R7}	$7.3I_m$	–	–	I_{R4}	$7.3I_m$	–	–
I_{R5}	$7.7I_m$	–	–	I_{R6}	$7.4I_m$	$3V_m$	$22.2V_mI_m$	I_{R5}	$7.3I_m$	–	–
I_{R1}	$8.1I_m$	$2V_m$	$16.2V_mI_m$	I_{R8}	$7.4I_m$	–	–	I_{R9}	$7.3I_m$	–	–
I_{R2}	$8.1I_m$	–	–	I_{R1}	$7.5I_m$	$1V_m$	$7.5V_mI_m$	I_{R8}	$7.5I_m$	$1V_m$	$7.5V_mI_m$

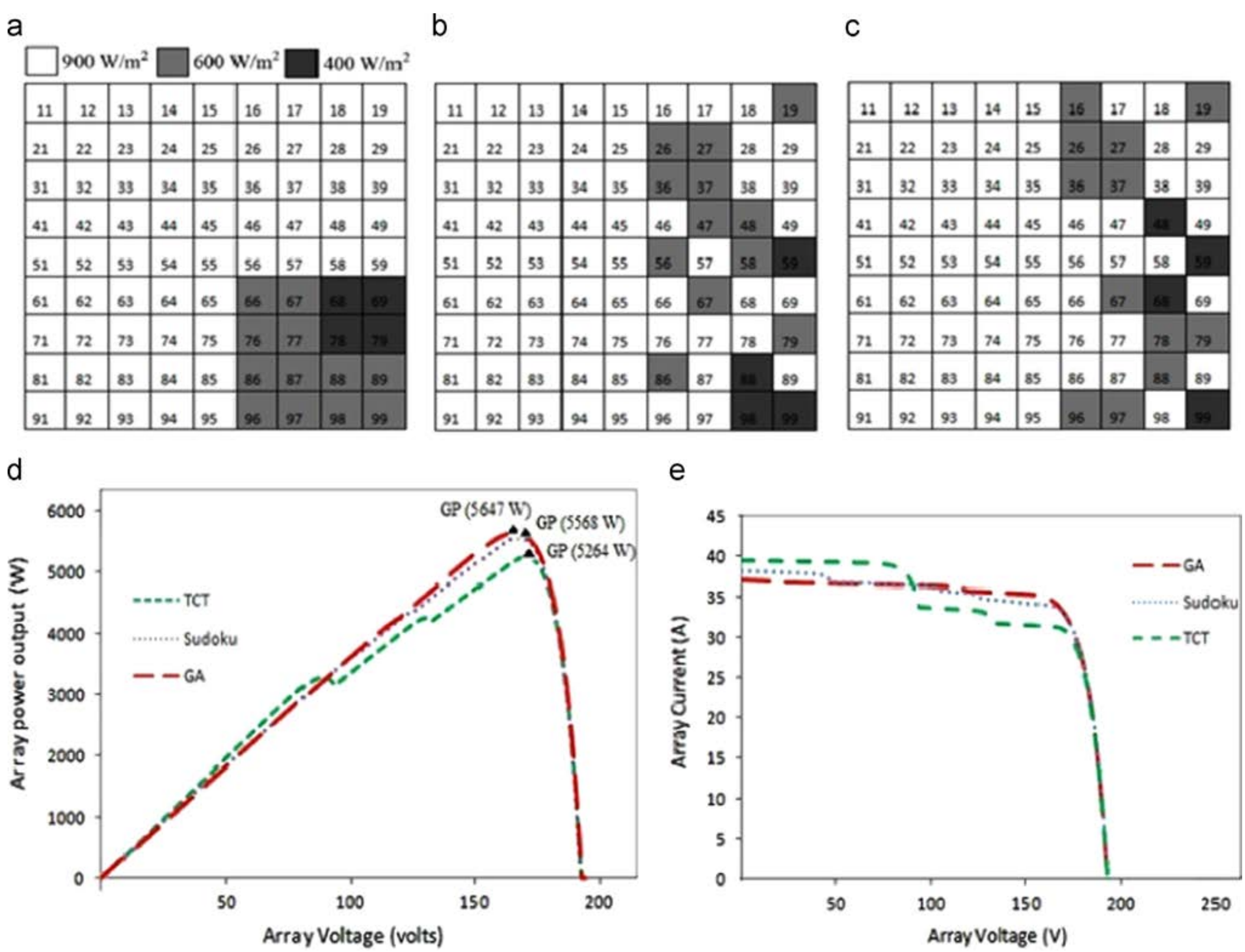

Fig. 5. Shading pattern for case3 (a) TCT interconnection scheme (b) Shade dispersion using Su Do Ku pattern (c) shade dispersion with GA arrangement (d) PV characteristics for TCT, Su Do Ku and GA arrangement (e) IV characteristics for TCT, Su Do Ku and GA arrangement.

Table 4
Location of GP in TCT, Su Do Ku and GA arrangement for Case 3.

TCT arrangement				SU DO KU arrangement				GA arrangement			
Row currents in order in which panels are bypassed		Voltage V_A	Power P_A	Row currents in order in which panels are bypassed		Voltage V_A	POWER P_A	Row currents in order in which panels are bypassed		VOLTAGE V_A	POWER P_A
I_{R8}	$6.1I_m$	$9V_m$	$54.9V_mI_m$	I_{R5}	$6.8I_m$	$9V_m$	$61.2V_mI_m$	I_{R6}	$7.3I_m$	$9V_m$	$65.7V_mI_m$
I_{R9}	$6.1I_m$	–	–	I_{R9}	$7.1I_m$	$8V_m$	$56.8V_mI_m$	I_{R8}	$7.3I_m$	–	–
I_{R6}	$7.3I_m$	$7V_m$	$51.1V_mI_m$	I_{R8}	$7.3I_m$	$7V_m$	$51.1V_mI_m$	I_{R1}	$7.5I_m$	$7V_m$	$52.5V_mI_m$
I_{R7}	$7.3I_m$	–	–	I_{R2}	$7.5I_m$	$6V_m$	$45.0V_mI_m$	I_{R2}	$7.5I_m$	–	–
I_{R5}	$8.1I_m$	$5V_m$	$40.5V_mI_m$	I_{R3}	$7.5I_m$	–	–	I_{R3}	$7.5I_m$	–	–
I_{R4}	$8.1I_m$	–	–	I_{R4}	$7.5I_m$	–	–	I_{R7}	$7.5I_m$	–	–
I_{R3}	$8.1I_m$	–	–	I_{R6}	$7.8I_m$	$3V_m$	$23.4V_mI_m$	I_{R9}	$7.5I_m$	–	–
I_{R2}	$8.1I_m$	–	–	I_{R7}	$7.8I_m$	–	–	I_{R4}	$7.6I_m$	$2V_m$	$15.2V_mI_m$
I_{R1}	$8.1I_m$	–	–	I_{R1}	$7.8I_m$	–	–	I_{R5}	$7.6I_m$	–	–

Table 5
Summary of output power for TCT, Su Do Ku and GA approach.

Case	Maximum power (W)		
	TCT	Su Do Ku	GA
1	3558	4169	4802
2	5050	5341	5444
3	5264	5568	5647

Table 6
Percentage increase in output power using 'GA' as compared to TCT and Su Do Ku pattern.

Case	Power enhancement using GA (%)	
	TCT	Su Do Ku
1	34.96	15.18
2	7.8	1.93
3	7.28	1.42

700 W/m^2, 400 W/m^2 and 300 W/m^2, respectively. The current limits of the individual row in this shading pattern do not vary significantly as the shading is less as compared to Case 1. The GA reconfigured pattern is shown in Fig. 4(c). The row currents are calculated in similar manner as in previous case. As explained earlier, the variation in the current limits of the rows for each pattern is a measure of uniformity in the shading dispersion. More is the variation, less uniform the shade dispersion would be. The current limit values of individual rows for TCT, Su Do Ku and GA reconfiguration schemes given in Table 3. clearly imply that the shade dispersion is more uniform in GA reconfigured pattern.

The effect of uniform shade dispersion is observed from the *I–V* curves. The curve is more linear for GA reconfigured pattern than the other two. Also, since the variation in the row currents reduces, current delivering capacities of the rows with minimum current limit increases, thus output power increases which is clear from *V–I* coefficients shown in Table 3. The combined effect of the above two is seen as a rise in output power as shown in *P–V* curve presented in Fig. 4(d).

Case 3. Short and narrow shadow.

The insolation levels considered for this case are 900 W/m^2, 600 W/m^2 and 400 W/m^2 as shown in Fig. 5(a). Unlike previous cases since a very small group of panels is subjected to partial shading the scope of maximizing output power is very less. Applying the similar analysis as done in previous two cases we obtained Table 4.

Similar to the Case 2 the variation in row current limit is very less for GA reconfigured pattern compared with other two patterns. Hence more uniform *I–V* characteristics and higher coefficients. The *P–V* curve confirms the rise in power.

5. Comparative analysis

This section provides a comparative study of the array output power for the TCT, Su Do Ku and the GA based approach for the shading patterns discussed above. For case1 (short and wide), it can be seen that the increase in power with GA based approach as compared to the TCT interconnection scheme is 1244 W. This amounts to a percentage increase of 34.96% which is quite large. Also, the power enhancement using GA approach as compared to the Su Do Ku puzzle arrangement is 633 W (15.18%).

For Case 2 (long and narrow), it can be seen from Fig. 4(d) that the GP for GA based reconfiguration technique is at 5444 W and that for the Su Do Ku and the TCT configurations are at 5341 W and 5050 W, respectively. As a result, the output power generated using GA approach is 7.8% and 1.93% more as compared to the Su Do Ku and the TCT pattern, respectively. Similarly, for Case 3 (short and narrow), it is evident that the GP for TCT scheme occurs at 5264 W whereas the GP for the Su Do Ku pattern is at 5568 W. The power output using the GA approach is found to be 5647 W giving a percentage increase of 7.28% and 1.42% as compared to the TCT and the Su Do Ku scheme. The above results are summarized in Tables 5 and 6.

As evident from the Table 5, the power generated using GA technique is higher as compared to the TCT and Su Do Ku pattern for all the three cases. However, it is observed from Table 6. that the percentage increase is more for Case 1 and less for the subsequent cases. The reason for this phenomenon is that the wide shading condition is experienced by the array in Case 1 whereas it is narrow shading condition for the other two cases. Therefore, it can be inferred that the benefit of reconfiguration is more if the panel is subjected to wide shading conditions.

6. Conclusion

This paper presents Genetic Algorithm based reconfiguration scheme for the arrangement of PV modules in a PV array which exhibits increased array power generation under partially shaded conditions. The reconfiguration technique involves changes in the electrical interconnections for shade dispersion keeping the physical location of the PV modules unchanged. The proposed approach achieves a fairly uniform distribution of the shadow all over the panel thereby avoiding concentration of shadow on any one row thus equalizing the row currents to a greater extent as compared to other two reconfiguration schemes. The system performance is analyzed for various shading conditions and it is proved that the proposed technique is superior and yields better results as compared to the TCT and Su Do Ku arrangement.

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