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Solar PV array reconfiguration using the concept of Standard deviation and Genetic Algorithm

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Abstract

Partial shading of PV arrays is one of the most discussed and worked upon problem in the field of solar photovoltaic as it reduces the output power and exhibits multiple peaks in the PV and IV characteristics. As, a result the modules have to be reconfigured to get a maximum power output. This paper 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 proposed technique utilizes, standard deviation genetic algorithm (SDGA) as an optimization tool, which gives the final connection matrix for the new electrical interconnection which extracts the maximum power from the PV array. This is done to obtain uniform shade dispersion throughout the panel. The proposed method has been tested and simulated in Matlab-Simulink environment under partial shading conditions. Results of the simulation show that the proposed reconfiguration technique exhibit superior results as compared to the traditional TCT interconnection scheme.

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Keywords: Array Reconfiguration; Partial Shading; Mismatch losses; SDGA; Global maximum power point; Power enhancement.

1. Introduction

Global warming and fossil fuel depletion has placed the development of sustainable energy sources on top priority of many nations. Solar photovoltaics are one of the most sought out sustainable energy sources due to the

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decreasing cost of photovoltaic cells and the improvements in the power conversion technology. Apart from being a clean and maintenance free, solar energy is especially appropriate for smart grids with distributed power generation which is indeed the next generation power network structure. A common phenomenon that arises in PV array is partial shading (PS). The phenomenon of partial shading may be due to building shade, birds, tress etc.. which reduces the overall output power of the system [1-3].

In order to achieve higher energy outputs from the PV systems, different array interconnection schemes have been proposed in literature to reduce the mismatch losses in the array. They are Series, parallel, SP, TCT, BL and HC [4]. It is found that TCT interconnection scheme ranks higher as compared to other schemes in terms of maximum of power, fill factor and to tackle the problem of mismatch losses under partial shading condition [5]. These inferences were however tied down by the results presented by the So Do Ku arrangement scheme with smooth increasing PV characteristic and higher power output [6] but the Su Do Ku reconfiguration technique has a few shortcomings. Firstly physical labor and excessive length of the interconnecting wires. Secondly, in this type of reconfiguration the first column of the array remains unaltered. Thus, a shade falling on the left side of the array will remain undispersed leading to a reduced power output and multiple peaks in the PV array. Finally, SuDoKu reconfiguration technique poses limitations on its applications to only a 9x9 matrix.

Considering the above facts, this paper proposes a unique electrical array reconfiguration technique. Electrical array reconfiguration is a technique in which the PV modules are rearranged dynamically by altering the electrical connections without physically moving the modules in order to increase the maximum power output. The EAR technique proposed in this paper utilizes Genetic algorithm for addressing the problems caused by partial shading of photovoltaic arrays. The algorithm aims at minimizing the standard deviation of individual row currents. This reduces the mismatch losses and at the same time increases the power output. The proposed optimization technique is implemented on a 9X9 PV array to get the interconnection matrix.

The performance analysis for different shading conditions shows that standard deviation based Genetic algorithm approach yields an improved output power as compared to the Sudoku reconfiguration scheme. Minimizing the standard deviation of individual row currents leads to elimination of multiple peaks in PV and IV characteristics, thus contributing to an improvement in the power output. This suggests that the proposed method provides a better shade dispersion as compared to TCT interconnection and Sudoku reconfiguration scheme.

1.1. Model of solar cell

In practical, one of the recent methods to maximize power is array reconfiguration. In this article aforementioned task is carried out using SDGA technique. To recognize the modelling simplicity, the single diode PV model constructed and used as shown in Fig.1.

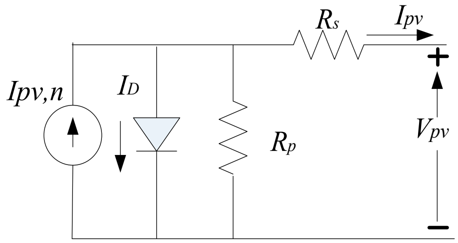


Fig.1. Schematic of One diode model.

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

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, 'R_s' is the resistance offered by the solar cells in the path of the current flow and 'R_{sh}' is the resistance offered to the leakage current.

2. TCT configured PV array

The TCT configuration is obtained by modifying the series parallel configuration is shown in fig . 2a. Cross ties are connected across each rows of the junctions. All modules in a column are connected in series and each module in a row has modules connected in parallel [7] . The PV array considered for study is a 9X9 array that is 81 panels are connected in TCT configuration is shown in Fig. 1a. The modules are labelled as 'r_c' where 'r' denotes the rows and 'c' denotes the column in which the module is connected. For instance label 45 represents that the module is connected in 4th row and 5th column. The current generated by the array at a given irradiance is given by

$$I = KI_m \tag{2}$$

where , 'I_m' is the current generated by the module at standard irradiance G_0 (1000W/m²) and $k=G/G_0$. . Therefore the current generated by the module is directly proportional to the solar irradiance on the panel. The voltage of the array is given by the sum of the voltages of the 9 rows.Applying the KVL,

$$V_a = \sum_{k=2}^{9} V_{mk} \tag{3}$$

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

$$I_a = \sum_{c=1}^{9} (Irc - I_{(r+1)}C) \text{ , r=1,2,3…9} \tag{4}$$

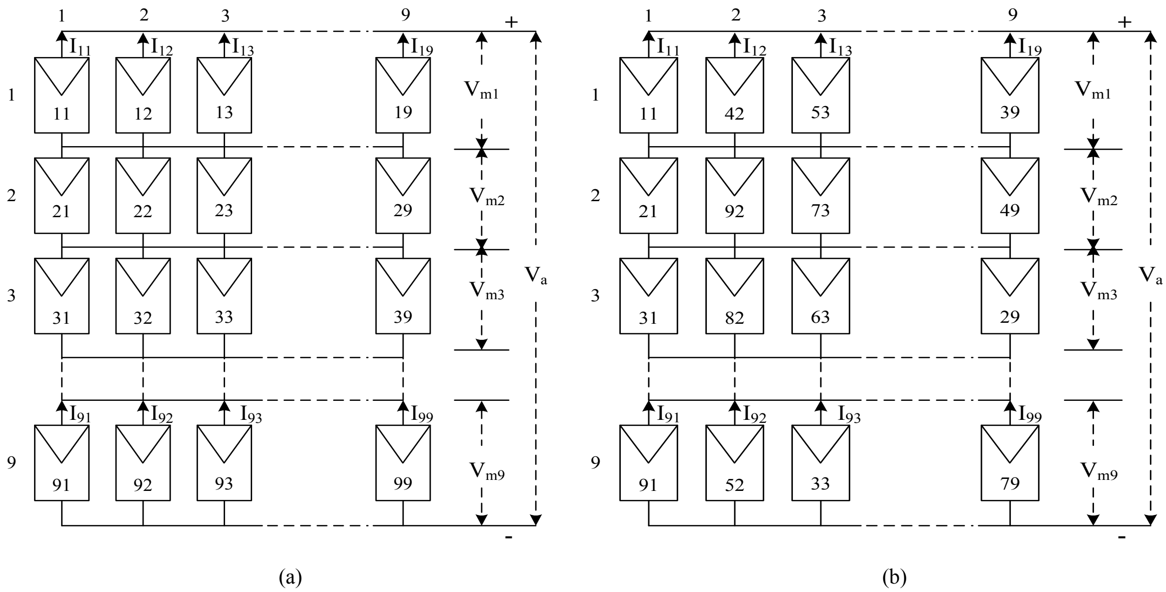


Fig. 2. Reconfiguration of PV array (a) TCT configuration scheme; (b) SuDuKo Configured PV Array.

3. Sudoku configured PV array

Sudoku is a logic-based combinatorial number placement puzzle. The puzzle consists of nine 9X9 arrays with a total of 81 cells. The objective of the puzzle is to occupy each cell with a number from 1 to 81 such that no number is repeated in a given row and column as well as the corresponding 9X9 matrix so as to provide a unique solution. In Sudoku reconfiguration technique the physical location of the modules is changed without changing the electrical connections between them which can be seen in Fig. 2b. This physical relocation of modules helps in uniform dispersion of the shading pattern with the help of the puzzle solution. However, this technique has some drawbacks. Firstly, physical relocation of the panels poses as a difficult and a laborious task. Secondly, excessive length of interconnecting wires for reconfiguration run the risk of being tampered thus jeopardizing the system reliability and hence adding to the maintenance cost. Thirdly, this method poses a limitation of being applicable to only a 9X9 matrix.

4. Proposed GA technique

A genetic algorithm based optimization technique has been proposed to solve the problem of array reconfiguration under partial shading conditions. Genetic algorithm is a search heuristic that mimics the process of natural selection which is used in computing to find true or approximate solution to optimization and search problems. It is based on Darwinian principle of survival of the fittest. The algorithm uses techniques inspired by evolutionary biology such as inheritance, mutation, selection and crossover.

Initially many individuals are randomly generated to form an initial population. The population size depends on the nature of the problem but typically contains many hundreds to thousands of possible solution. In the next process of selection, a proportion of the existing population is selected to breed a new generation. Solutions with higher fitness values are duplicated with greater probability whereas solutions with a lower fitness function are discarded. The next steps in creating a new population is mating and crossover. A child solution is created by a pair of parent solutions which are selected for breeding from the fitness pool generated previously. The new child solution generated share many characteristics of its parents. After selection and crossover, the next step is mutation. Selection and crossover steps only exploit the already known areas of the search space, which could lead to premature convergence. Mutation ensures that the individuals are not exactly same, thus bringing in some new information to the set of the genes. Mutation is essential to preserve a genetic diversity in the population in order to exploit the entire search space and converging at a global optimum.

Genetic algorithm is most suitable for continuously changing environment conditions, thus it finds its application to problems of solar energy which is inherently dynamic and intermittent in nature. The optimization technique proposed earlier in [8] utilizes Genetic Algorithm for electrical array reconfiguration. Though the technique has proven to be a better alternative to the Sudoku reconfiguration, yet it has some shortcomings which can be elucidated as follows. The objective function defined for maximization depends on predefined weight vectors W_e and W_p which are assumed for individual row currents and panel output power respectively. Moreover, the random generation of crossover and mutation probability may affect the convergence of the algorithm about a global optimum.

Therefore, it is necessary to formulate a new GA based technique which takes into consideration, the above mentioned complexities. The newly proposed GA based technique in this paper the concept of standard deviation for optimization. Mathematically, standard deviation is a measure that is used to quantify the amount of variation or dispersion of a set of data values. A low value of standard deviation signifies that the data points tend to be close to the average or the mean of the set, while a high standard deviation indicated that the data points are spread out over a wide range of values. Minimizing the standard deviation of the row currents can reduce the mismatch losses, eliminate multiple peaks and increase the power output of the PV array. Therefore the objective function for the above array reconfiguration problem can be defined in such a way so as to minimize the standard deviation

$$\max imize(fitness(i)) = \frac{1}{1+\sigma_1} \tag{5}$$

Where,

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

(ii) $\sigma_1 = \sqrt{\frac{1}{N}\left[\sum_{j=1}^{N}(I_j - I_m)^2\right]}$ Where, ‘ σ_1 ’is Standard deviation of individual row currents and ‘N’ is the number of rows,

$$I_m = \frac{1}{N}\sum_{j=1}^{N} I_j$$

‘ Ij’ is the current of the jth row. Therefore, it can be seen that the objective function of the proposed technique is better as compared to the earlier method in the following ways. Firstly, it is uncomplicated and only depends on the values of individual row currents. Secondly, it does not involve random assumption of weight vectors.

The proposed reconfiguration algorithm is tested on MATLAB/Simulink. The pseudo code for the proposed reconfiguration algorithm is as follows:

Initialize input parameters*:*
Irradiation pattern, population size, maximum number of iterations (generations), crossover and mutation probability.
Start:
Generate *initial population*
For *each member,*
    Evaluate fitness function= $\dfrac{1}{1+\sigma_1}$
end
For *iter=1:N*
    Selection *of parents using roulette wheel selection;*
    Crossover *of parents using the specified crossover probability;*
    Mutation *of resulting offspring at the specified mutation probability;*
    Evaluation *of new candidate fitness function*
    Selection of individuals for next generation
end

5. Results and Discussion

A 9X9 PV array is connected in TCT configuration and subjected to Short Wide shading patterns to evaluate the performance of the proposed GA based reconfiguration method. The results are verified by simulating the different reconfiguration techniques in MATLAB/Simulink environment. Kotak PV 80 W panel is used for simulation. The results obtained are compared with TCT and Sudoku reconfiguration techniques for the giving shading patterns. Further PV and IV curves are also plotted for comparative analysis of TCT, Sudoku and GA based reconfiguration technique (SDGA).

Case 1: Short and wide and wide shadow:

A PV array is divided into four groups of different insolation. The groups receive an insolation of 900 W/m^2, 600W/m^2, 400W/m^2 and 200W/m^2 respectively. Since all the columns and only a few number of rows are subjected to shading therefore this shading pattern is referred to as short-wide. Fig. 2. shows the irradiation pattern corresponding to Case 1.Row currents are to be calculated to find the location of GP. It can be seen from Fig. 1. that the panels in row are connected in parallel. Hence, the maximum possible output current is given by the sum of the current limits of individual panels. For the first row of TCT configuration, the current limit can be calculated as

$$I_{R1} = K_{11}I_{11} + K_{12}I_{12} + K_{13}I1_{3} + K_{14}I_{14} + K_{15}I_{15} + K_{16}I_{16} + K_{17}I_{17} + K_{18}I_{18} + K_{19}I_{19} \tag{6}$$

Where K_{1c}=G_{1J}/G_0(c=column index) where G_{1J} is the irradiance and I_{1c} is the current limit for full irradiance (G_{1J}=G_0) of the panel labelled 1J. Let I_m be the current limit for the panels for full irradiance (K_{1c}=1)under standard temperature and conditions. It can be assumed that all the solar panels in the array are identical.

Hence $I_{11} = I_{12} = I_{13} = ... = I_{19} = I_m$

For shading pattern shown in figure(reference) panels in 1 to 5 rows receive the same insolation(G=900 W/m^2).Hence the limiting current of the 5 rows can be calculated as;

$$I_{R1} = I_{R2} = I_{R3} = I_{R4} = I_{R5} = 9*0.9I_m = 8.1I_m \tag{7}$$

Where K_{1c}=900/1000=0.9

In row 6 , an insolation of 600 W/m^2 is incident on the first 4 panels and 900W/m^2 for the last 4 panels. Therefore the limiting current can be calculated as

$$I_{R7} = I_{R8} = I_{R9} = 3*0.6I_m + 3*0.4I_m + 3*0.2I_m = 3.6I_m \tag{8}$$

Similarly the currents contributed by the subsequent rows is given by

$$I_{R7} = I_{R8} = I_{R9} = 3*0.6I_m + 3*0.4I_m + 3*0.2I_m = 3.6I_m \tag{9}$$

The current contributed by different rows vary according to 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

$V_a = 8V_m + V_d$, where V_d is the voltage across the diode

Since $V_d << V_a$, we neglect V_d

Therefore $V_a = 8V_m$ (10)

The output given by the array if no array is bypassed is given as $P_a = (9V_m)I_m$ (11)

Respective voltages and corresponding powers of the array are calculated in table 1 according to the order in which the arrays are bypassed.It is observed that maximum power is extracted from the array, only when rows 6, 7, 8, and 9 are bypassed, because the location of GP is far away from the nominal voltage of the array. As more rows are bypassed with the increasing load requriements, the array voltage drops down to $5V_m$ in which the maximum power is extracted. Further , It can be observed that the maximum power generated by the array is 3348 W and the GP occurs at 109.4 V which is less than the nominal voltage of the array.

Considering for SuDoKu configuration, the shade is uniformly dispersed. The individual row currents and respective power values are calculated in the table 1. It can be clearly seen from the simulation that the array voltage has improved and is close to the nominal voltage of the array. The power output for SuDoku is 4532W which is higher than that obtained for TCT configuration.

The proposed GA based reconfiguration is validated using the same 9 X 9 PV array which is subjected to the same Short Wide shading pattern. The entire PV array is reconfigured using the proposed technique to uniformly distribute the effect of shading. Therefore, the current in each row is given by

$$I_{r1} = 6*0.9I_m + 2*0.4I_m + 0.2I_m = 6.4I_m$$

$$I_{r3} = I_{r4} = I_{r5} = I_{r8} = 6*0.9I_m + 0.6I_m + 2*0.4I_m = 6.4I_m$$

$$I_{r6} = 4*0.9I_m + 4*0.6I_m + 0.4I_m = 6.4I_m$$

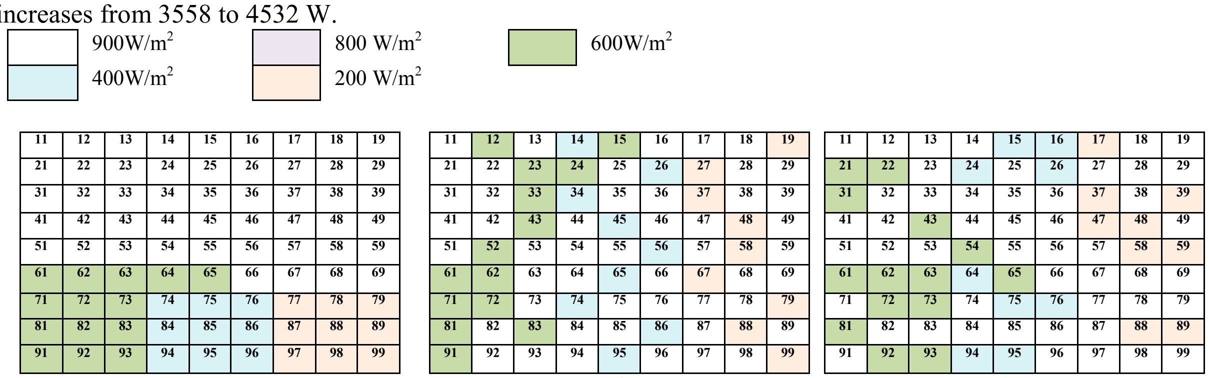
$$I_{r2} = I_{r7} = I_{r9} = 5*0.9I_m + 2*0.6I_m + 2*0.4I_m = 6.5I_m$$

Therefore it can be seen that,

$$I_{r1} = I_{r3} = I_{r4} = I_{r5} = I_{r6} = I_{r8} \quad (12)$$

$$I_{r2} = I_{r7} = I_{r9} \quad (13)$$

Simulation results show that 6 of the 9 rows contribute same current ,i.e $6.4I_m$ and the remaining 3 contribute $6.5I_m$. The standard deviation of the row currents for SDGA reconfiguration is $0.05I_m$ as opposed to $0.1581I_m$ of SoDoKu and $2.1794I_m$ of TCT configuration. It is evident from the stepless IV characteristics that a reduced standard deviation of the row currents has minimized the mismatch losses leading to an increase inthe ouput power from 4532W of Soduko to 4826W are shown in Fig. 4. (a). As compared to TCT arrangement, the output power increases from 3558 to 4532 W.

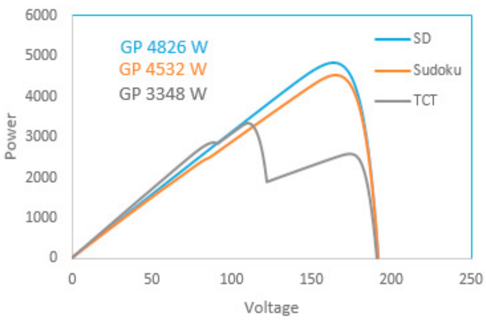


(a) (b) (c)

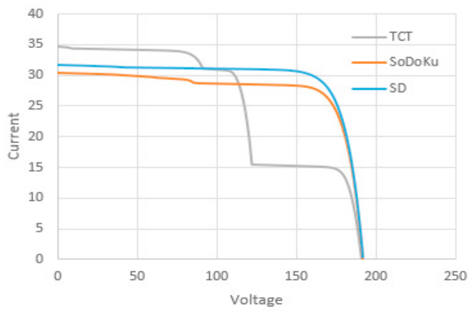
Fig. 3. Shading Pattern for case1 (a) TCT configuration scheme; (b) shade dispersion using SUDOKU reconfiguration scheme; (c) shade dispersion using proposed SDGA.

Table 1. Location of GP in TCT, SuDoKu and SDGA arrangement for Case1

TCT arrangement				Su Do Ku arrangement				SDGA arrangement			
Row current in the order in which panels are bypassed		Voltage V_a	Power P_a	Row current in the order in which panels are bypassed		Voltage V_a	Power P_a	Row current in the 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}	$6.3V_mI_m$	$9V_m$	$56.7V_mI_m$	I_{R1}	$6.4I_m$	$9V_m$	$57.6V_mI_m$
I_{R8}	$3.6I_m$	-	-	I_{R7}	$6.3V_mI_m$	-	-	I_{R3}	-	-	-
I_{R7}	$3.6I_m$	-	-	I_{R8}	$6.3V_mI_m$	-	-	I_{R4}	-	-	-
I_{R6}	$6.6I_m$	$6V_m$	$39.6V_mI_m$	I_{R1}	$6.3V_mI_m$	-	-	I_{R5}	-	-	-
I_{R5}	$8.1I_m$	$5V_m$	$40.5V_mI_m$	I_{R2}	$6.5V_mI_m$	$5V_m$	$26.4V_mI_m$	I_{R6}	-	-	-
I_{R4}	$8.1I_m$	-	-	I_{R4}	$6.5V_mI_m$	-	-	I_{R7}	-	-	-
I_{R3}	$8.1I_m$	-	-	I_{R3}	$6.5V_mI_m$	-	-	I_{R2}	$6.5I_m$	$3V_m$	$19.5V_mI_m$
I_{R2}	$8.1I_m$	-	-	I_{R5}	$6.5V_mI_m$	-	-	I_{R8}	-	-	-
I_{R1}	$8.1I_m$	-	-	I_{R9}	$6.5V_mI_m$	-	-	I_{R9}	-	-	-



(a)



(b)

Fig. 4. (a) Case 1: PV Characteristics for TCT, SuDuKo and SDGA arrangements; (b) Case 1: IV Characteristics for TCT, SuDuKo and SDGA arrangements.

Table 2.Output Power obtained for TCT, SuDoKu and SDGA

Case	Maximum power(W)		
	TCT	Sudoku	SDGA
1	3348	4532	4826

Table 3.Percentage increase in Power using SDGA approach as compared to TCT and SuDoKu reconfiguration scheme

Case	Power enhancement using SDGA (%)	
	TCT	Sudoku
1	44.14	6.5

It can be seen in Table 2 that there is 1478W increase in power for SDGA based approach as compared to TCT configuration. This amounts to 44.14% percentage improvement which is quite considerable. Also there is a power enhancement of 294W (6.5%) using SDGA based approach as compared to Sudoku arrangement can be seen in Table 3.

6. Conclusion

This paper presents a new genetic algorithm based electrical array reconfiguration method inorder to increase power generation of a solar PV under partial shading conditions. In this method , the electrical interconnections of the modules are altered whereas the physical location of the modules remains unchanged. The proposed approach aims at equalizing the individual row currents by minimizing the standard deviation. This makes it feasible to reduce the mismatch losses and extract maximum power from array under any environmental conditions. For the given shading pattern, it is found there is 44.14% increase in the maximum power using the proposed technique. The system performance is analyzed, and it is proved that the proposed technique yields better results as compared to the TCT interconnection scheme.

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