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A shade dispersion interconnection scheme for partially shaded modules in a solar PV array network

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A B S T R A C T

Solar Photovoltaic (SPV) arrays are networks of many modules interconnected to provide required terminal voltage and current. In field conditions, large PV arrays deliver lower power than array rating. In this paper, sensitivity of modular interconnection schemes in variation of available power from PV array is investigated. The approach involves the development of a computer algorithm that is required to evolve the new connection scheme to maximize power under all shading conditions. Connection schemes corresponding to minimum power loss for several shadows which are synthetized and an innovative connection scheme is evolved. This connection scheme is considered as the optimal connection scheme. The emerged connection scheme is evaluated for a small SPV array of size 3 × 3 and a comparatively large SPV array of size 7 × 7 using a prototype field experiment for various possible shading patterns. The merit of its energy generation compared to earlier interconnection schemes is highlighted. It is found that the proposed connection scheme excels in performance and redundancy over the hitherto known best interconnection schemes. The scheme may be very conveniently applied to subarrays which in turn can be synthesized for larger SPV arrays.

1. Introduction

Solar Photovoltaic (SPV) arrays are networks of many modules interconnected to provide terminal voltage, current rating and desired power. It has been found that, in field conditions, the array delivers output power less than the sum of power generated by constituent modules. The power loss could be due to various faults in arrays such as manufacturer tolerance in cell/module characteristics, module temperature rise, detachment of strings due to stress and shadow problems. Mismatch for a long period leads to reduction in efficiency of SPV array, creates hotspots and reduces lifespan of SPV modules. The current and voltage output of SPV array made of series and parallel connected modules respectively gets limited by mismatch due to shaded modules in the array [1,2]. The effect of electrical mismatches on the performance of a SPV array has been investigated earlier for both terrestrial and satellite born SPV system [3–7]. In this regard, series paralleling, wherein, a branch circuit is divided into series blocks has been studied to reduce the effect of electrical mismatches [7–10]. In recent years, it has been realized that the effect of mismatch can be substantially reduced by a proper arrangement of cellular interconnection in the modules. Series-Parallel (SP), Bridge Linked (BL), Total Cross Tied (TCT) and Honey Comb (HC) type of interconnection schemes have been investigated [11–17]. The investigations have shown that TCT and BL arrays excel over other connection schemes. More recently, a fixed interconnection scheme in order to disperse the shading effect throughout the array is proposed in the literature [18]. The connection scheme is tested using solar cells and found to be effective than other conventional interconnection schemes but in case of modules, the results may varies due to internal mismatches. Interconnection based on Futoshiki puzzle pattern is proposed in literature [19] in which physical location of SPV modules of array is altered without changing the electrical connection of modules. Another reconfiguration technique of modules in PV arrays based on Sudoku patterns has been proposed in literature [20]. In order to overcome the disadvantages of rearranging the PV modules position according to Sudoku, a new technique called as optimal Sudoku has been proposed in literature [21]. A physical rearrangement of PV modules of array using Magic Square configuration has been proposed in literature [22]. The positioning of PV modules to reduce line losses and mismatch losses of PV array so as to disperse the effect of partial shading has been proposed in

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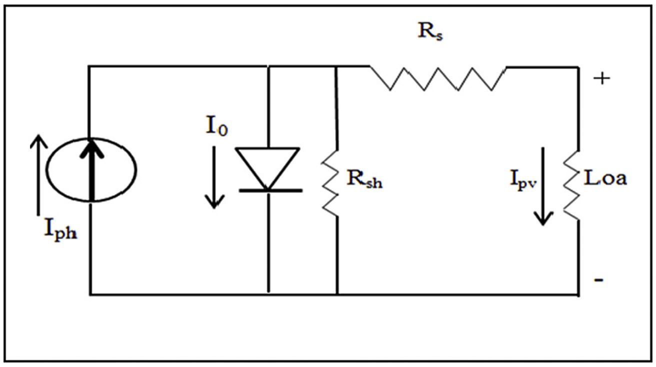


Fig. 1. Equivalent circuit of a SPV cell.

literature [23]. These methods rather become complicated when a SPV array of larger size is considered and also the rearrangement of PV modules depends upon the shading structure. Power enhancement from PV array under partial shading conditions using various optimization techniques such as Ant Bee colony, Genetic Algorithm have been proposed in literature [24–26].

In this paper, an approach is proposed for connection of modules in PV arrays based on renumbering of modules and is studied for a small SPV array of size 3 × 3 and a comparatively large SPV array of size 7 × 7. The study has been done with and without bypass diodes under various types of possible shadow patterns with different size and location. The interconnection scheme is named as Shadow Dispersion Scheme (SDS) and it exhibits minimum power loss. Furthermore, the efficacy of this scheme is investigated for subarray up to 2.5 KW as a consequence of which large arrays could be constructed from such constituent sub arrays.

2. System configuration

2.1. Modeling of solar PV cell

Generally, a SPV cell is a current generator consists of a diode in parallel which is represented by an equivalent circuit as shown in Fig. 1.

The photo current of the cell is represented by a current source I_{ph}. R_s and R_{sh} are the internal series and shunt resistances respectively. Usually R_s value is very small as compared to large value of R_{sh}, so these are neglected. SPV module is designed by connecting a number of SPV cells in series. A is the ideality factor. I_{PV} is the generated current. V_{PV} is the SPV voltage. 'q' is the charge of electron (1.6×10^{-19} C).

The mathematical modeling of SPV cell can be done using the given equation.

$$I_{PV} = I_{ph} - I_o\left[\exp\left(\frac{V_{pv} + R_s I_{pv}}{A}\right) - 1\right] - \left[\frac{(V_{pv} + I_{pv}R_s)}{R_{sh}}\right] \tag{1}$$

2.2. Interconnection schemes

Interconnection schemes of SPV module refer to configuration in which modules are interconnected in an array. Several interconnection schemes have been proposed and tested which includes Series-Parallel (SP), Bridge Linked (BL) and Total Cross Tied (TCT); the three widely used interconnection schemes shown in Fig. 2. SP connection consists of a combination of number of series connected SPV modules in a string and number of such strings connected in parallel. When ties are connected across each junction of the SPV modules, TCT is obtained. The BL connection can be formed by connecting the modules in a bridge rectifier form.

2.3. Impact of bypass diodes on partial shading

During shading, the current of unshaded PV modules flow through the shaded modules that can result in damage of the shaded modules. So, to avoid this situation, bypass diodes are connected in parallel with the modules in order to bypass the extra current produced by the unshaded modules through them as shown in Fig. 3. Bypass diodes can help to protect the PV modules from the destructive effects of mismatching among PV modules. Series diodes called as Blocking Diodes are employed in PV modules so as to prevent the reverse power flow during non-sunshine hours [Fig. 3].

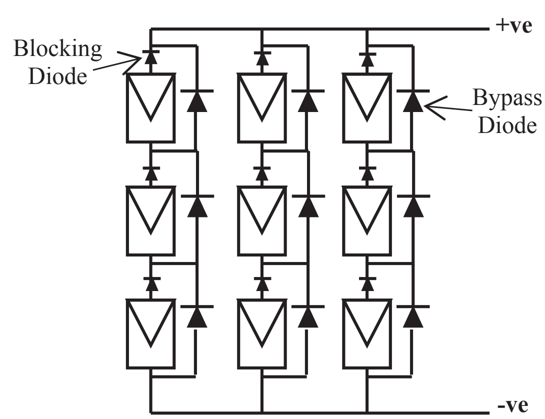


Fig. 3. Implementation of Bypass Diodes and Blocking Diodes in PV modules.

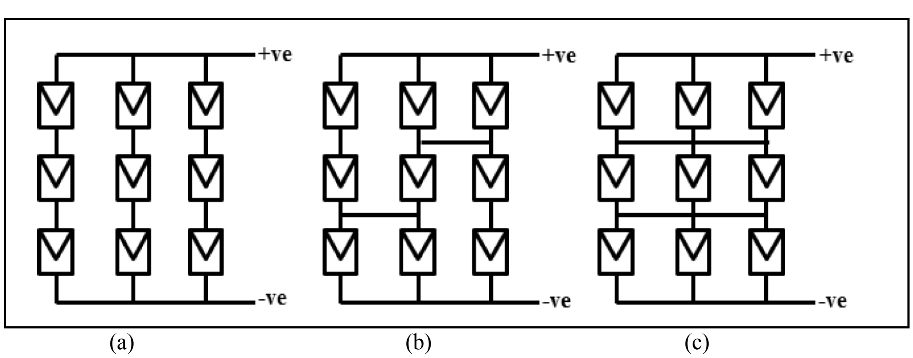


Fig. 2. Different Connection schemes of SPV array. (a) Series-Parallel (SP). (b) Bridge Linked (BL). (c) Total Cross Tied (TCT).

2.4. Effect of mismatch loss

Basically, mismatching is nothing but the power loss within the cells or modules of SPV array due to several factors such as difference in manufacturing of solar cells, soiling, irregular irradiance received by cells or modules, breaking of cells and partial/complete shading. These effects can cause both internal and external mismatch among modules of SPV array.

Internal Mismatches refers to the variation in parameters of SPV module due to certain change in physical conditions such as variations in cell manufacturing. These variations can affect the series resistance (R_S), shunt resistance (R_{Sh}), thermal voltage (V_T) and reverse saturation current (I_O).

External Mismatches refers to conditions that causes a decrease in the current output (photo current Iph) of SPV modules most commonly due to breaking of cells and partial/complete shading. These factors can reduce the power output to the highest by affecting its current output. As a result, the high current output of unshaded modules of an array gets imposed upon the unshaded modules connected in series that force them to get reverse biased and dissipates power.

In this paper, the internal mismatch is not considered rather the external mismatch among modules of SPV arrays are studied under various artificial shadow patterns. The external mismatch is studied as changing the configuration of cells in PV modules which is quite impractical in field condition where large arrays are considered.

3. Methodology for interconnection of SDS configuration

Shadow Dispersion Scheme (SDS) can be obtained by the algorithm proposed that starts with renumbering of the SPV modules. The connection of the modules is done only after renumbering. The algorithm aims to reduce the mismatch losses caused due to partial shading by dispersing its effect on the whole array utilizing a fixed arrangement for all shading patterns. The renumbering is done in such a way that the current entering at different nodes is equal. The main aim of changing the electrical configuration of the array is to disperse the current generated by unshaded PV modules of a string to other unshaded strings without affecting the shaded modules so as to extract maximum power. The PV modules in the row of other interconnection schemes are present in different rows in SDS. In SDS configuration, the effect of shading on single row has been reduced by distributing the effect in the whole array. So, the incoming current in a particular node can be increased and bypassing of PV modules can be decreased by using SDS configuration so as to increase the power generation during shading. The flowchart for rearranging the modules of SPV array is shown in Fig. 4.

First, a matrix M of size (a x b) of unconnected PV modules has been considered. The algorithm renumbers the PV modules in order to distribute the effect of partial shading throughout the array. The connection is done only after renumbering of PV modules in the array. The connection is done in such a way that different nodes have equal amount of current flowing through them. The new rearranged matrix is named as N (a x b). In both the matrixes, a and b denotes number of rows and columns respectively. In this algorithm, the modules of PV array have been divided into various different subarrays having different row symbols. So, there will be “a” numbers of maximum PV modules present in each subarray. So, the subarray size will be $k \times k$where $k = \lfloor\sqrt{a}\rfloor$. The symbols of PV modules of first column are kept unchanged and are taken as reference. The row symbols of next column are changed to$(I+k)$. This indicates that there are no PV modules with matching row symbols in same row. Then, in the next column, the row symbols are renumbered as$(I+2k)$. And so on. The renumbering will continue up to bth column for the case when “a” is not exactly divisible by “k”.

Now, for the case when “a” is exactly divisible by “k”, the process will continue up to the situation when there will be no repetition of row symbols for two PV modules in a row. This indicates that one cycle of renumbering is completed where one cycle is for (a/k) columns. In whole, the total numbers of cycle occurs is $N_r = [b/(a/k)]$. In every cycle, “m” is added in the process (i.e. $(j-1)\times k$) for every new cycle where “m” is increased by one i.e. “m+1”. The value of “m” is taken as zero for first cycle, one for second cycle and so on.

The steps involves in formation of new renumbered modules of SPV array is explained below.

Step1 Enter the number of rows and column as a and b respectively.
Step2 Calculate k = $\lfloor\sqrt{a}\rfloor$, where k takes the integer value only.
Step3 Calculate $z = a \bmod k$ (or a % k that gives remainder on division of a by k).
Step4 If$z\neq 0$, then $y=(j-1)k+i$, if $y>a$, then $y = y \bmod a$ and if $y<a$ then $y=a$, then store the value of M_{ij} to N_{yj} for all i = 1 to a, j = 1 to b and k = 1 to a.
Step.5 If z = 0, then divide b columns into r number of groups i.e. $N_r = [b/(a/k)]$where, r is the integer part only. If b mod (a/k) ≠0, then (r-1) groups will have a/k columns in each and rth group will be in the remaining columns. Else, (a/k) columns will be there in every group uniformly. Then $y = [(m-1)+i+(j-1)k]$where, m ranges from 1 to r. If$y>a$, then y = ymoda and if $y=0$ then, $y=a$. Then, $N_{yj} = M_{ij}$ where k and i ranges from 1 to a and j ranges from 1 to b. Thus, modules having same row indices are connected in parallel and first column modules are connected in series in the new matrix (renumbered matrix).

The connection technique for 3 × 3 and 7 × 7 SPV array is explained below. The connection is derived from TCT connection but have less number of ties than that of TCT.

3.1. Shadow Dispersion Scheme for 3 × 3 SPV array

The interconnection is done only after renumbering of modules using the flowchart framed above in Fig. 4. In this.

- a = b = 3. So, k = $\lfloor\sqrt{3}\rfloor$ = 1 (integer part of 1.72).
- z = 3 mod 1 = 0 (remainder of 3/1).
- As z = 0, the row indices of modules in first three column (a/k = 3) are renumbered uniformly.
- Modules of first column remain same as y = i.
- Modules in second column (M_{i2}) are renumbered as N_{y2}, where y = i+1.
- Likewise, modules of third column (M_{i3}) are renumbered as N_{y3} where y = i+2 for all i = 1 to a.
- Finally, modules having same row indices i.e. 11, 12 and 13 are connected in parallel and modules in first column i.e. 11, 21, 31 are connected in series.
- The positive and negative terminal of the array is taken out from both the ends of first column i.e. 11 and 31 respectively.

The initial and rearranged unconnected modules of the 3 × 3 SPV array is shown in Fig. 5 (a) and (b) respectively.

The TCT connection of the 3 × 3 SPV array is shown in Fig. 6 (a). The connection scheme for SPV array after renumbering the modules is explained and shown is Fig. 6 (b). As this is a fixed

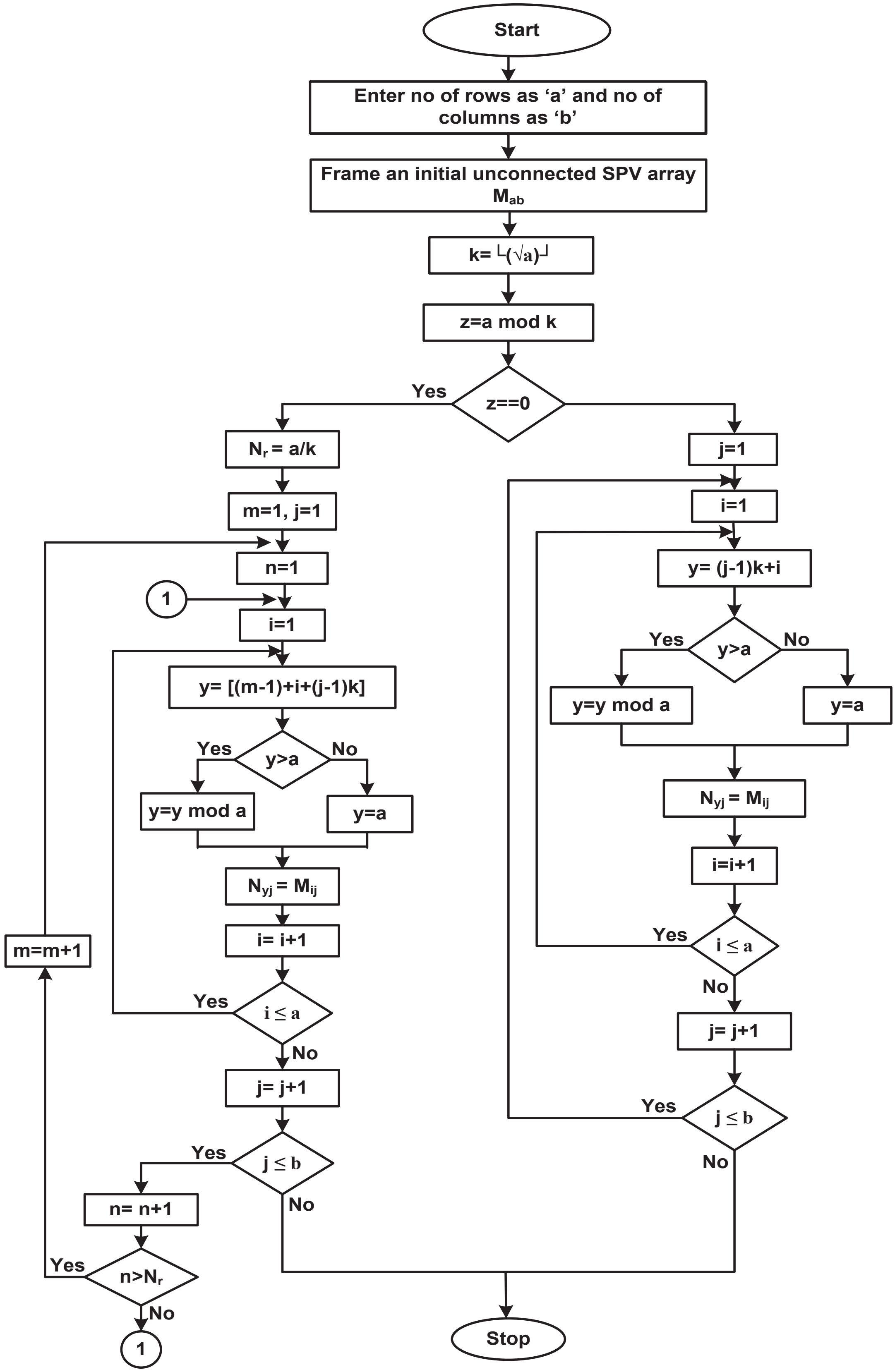


Fig. 4. Flow chart for renumbering the modules of SPV array.

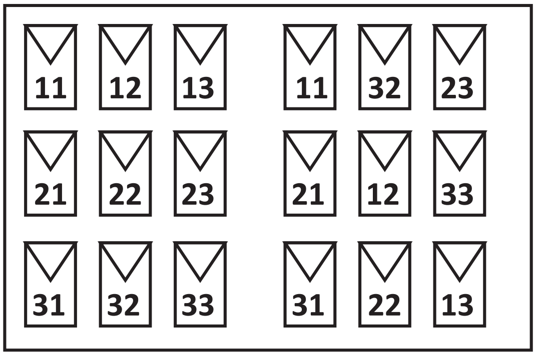


Fig. 5. (a) Initial unconnected modules of 3 × 3 SPV array. (b) Renumbered modules of 3 × 3 SPV array.

connection scheme for all type of shading patterns, the modules are kept unaltered. Only the modules are renumbered using flowchart as shown in Fig. 5.

The modules numbered as 11, 12 and 13 are connected to the positive terminals represented by red lines. After that, they are connected in parallel to each other as represented by blue lines. The modules numbered as 21, 22 and 23 are connected in series with modules numbered as 11, 12 and13 respectively represented by green lines. Modules numbered as 21, 22 and 23 are connected in parallel with each other represented by orange lines. Modules numbered 21, 22 and 23 are connected in series with the modules numbered as 31, 32 and 33 respectively represented by pink lines. Finally, the modules numbered 31, 32 and 33 are connected to negative terminal represented by black lines. The schematic diagram of 3 × 3 SDS topology of SPV array after rearrangement and connection [Fig. 6(b)] is shown in Fig. 6 (c).

3.2. *Shadow Dispersion Scheme for 7 × 7 SPV array*

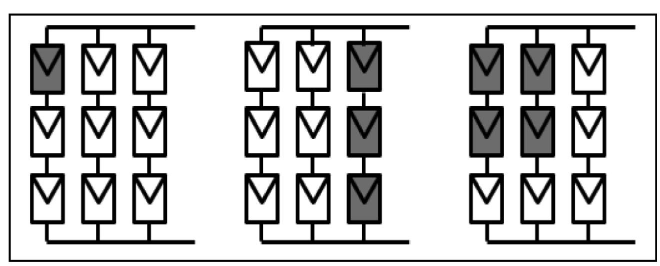
Likewise 3 × 3 SPV array, the modules can be renumbered using the flowchart. In this case.

- $a = b = 7$. So, $k = \lfloor\sqrt{7}\rfloor = 2$ (integer value of 2.64).
- $z = 7 \bmod 2 = 1$ (remainder of 7/2).
- As $z \neq 0$, the row indices of modules in first seven column ($a/k = 3.5$) are renumbered uniformly.
- Modules of first column remain same as $y = i$.
- Modules in second column (M_{i2}) are renumbered as N_{y2}, where $y= (j-1)\,k + i$.
- Likewise, modules of third column (M_{i3}) are renumbered as N_{y3}, where $y = 2k + i$ for all $i = 1$ to a.
- Similarly, modules of fourth column (M_{i4}) are renumbered as N_{y4}, where $y = 3k + i$ for all $i = 1$ to a.
- Modules of fifth column (M_{i5}) are renumbered as N_{y5} where, $y = 4k + I$ for all $i = 1$ to a.
- Modules of sixth column (M_{i6}) are renumbered as N_{y6} where, $y = 5k + I$ for all $i = 1$ to a.
- Modules of fifth column (M_{i7}) are renumbered as N_{y7} where, $y = 6k + I$ for all $i = 1$ to a.
- Finally, modules having same row indices i.e. 11, 12, 13, 14, 15, 16 and 17 are connected in parallel and modules in first column i.e. 11, 21, 31, 41, 51, 61 and 71 are connected in series.
- The positive and negative terminal of the array is taken out from both the ends of first column i.e. 11 and 71 respectively.
- Then, the connection is carried out like section 3.1 as per the TCT connection of 7 × 7 SPV array.

4. Spectrum of shadings

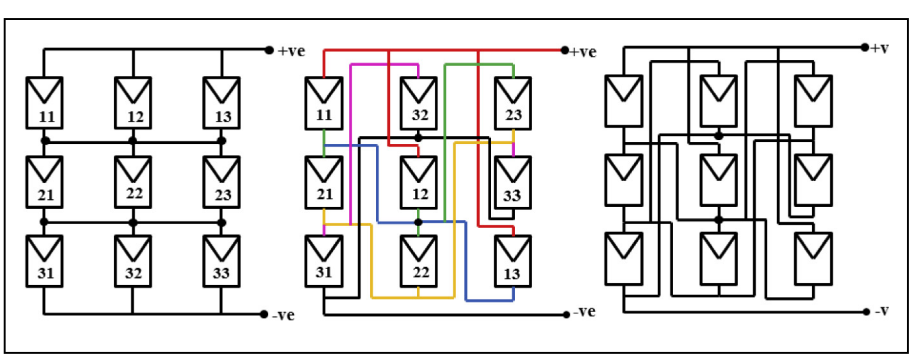
The SDS is verified for several shading patterns with varying size and location of the collector area for 3 × 3 SPV array and 7 × 7 SPV array. These shadow patterns cover all possible variations of shading on the collector surface.

Three types of shading patterns are considered for 3 × 3 SPV array namely One Module Shading, Long Narrow Shading and Short Wide Shading as shown in Fig. 7 (a), (b) and (c) respectively. These types of shading affect the power output to the most even if the unshaded modules are operating under good conditions. Similarly, five types of shading patterns are considered for 7 × 7 SPV array namely Short Wide Shading, Long Narrow Shading, Center Shading, L pattern Shading and One Module Shading as shown in Fig. 8 (a),



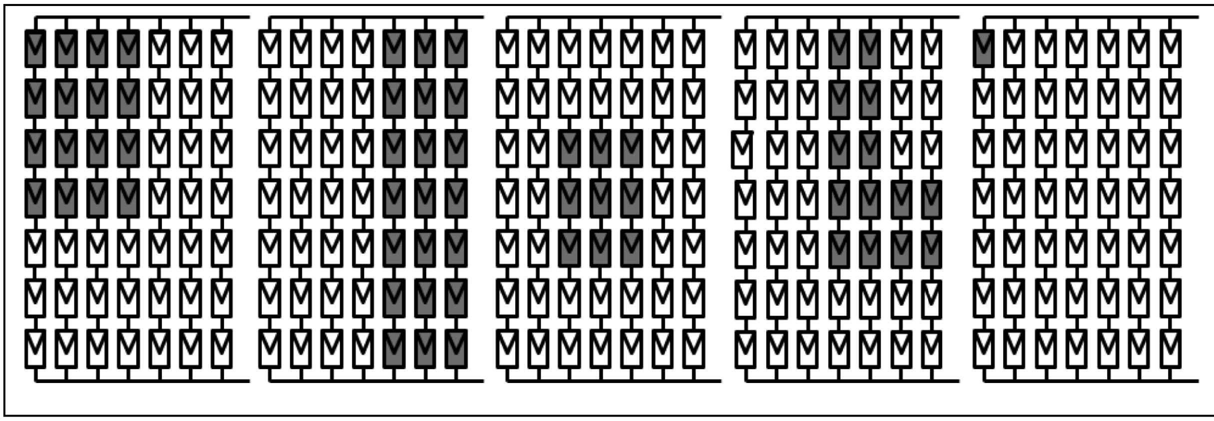
(a) (b) (c)

Fig. 7. Shading patterns for 3 × 3 SPV array. (a) One Module Shading. (b) Long Narrow Shading. (c) Short Wide Shading.



(a) (b) (c)

Fig. 6. (a) TCT connection of 3 × 3 SPV array. (b) SDS connection after renumbering of modules for 3 × 3 SPV array. (c) Final SDS connection of 3 × 3 SPV array.



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

Fig. 8. Shading patterns for 7 × 7 SPV array. (a) Short Wide Shading. (b) Long Narrow Shading. (c) Center Shading. (d) L Pattern Shading. (e) One Module Shading.

(b), (c), (d) and (e) respectively.

5. Formulations for mismatch loss

During shading, SDS yields more power and efficiency than conventional TCT connection. To prove this mathematically, a 7 × 7 PV array with a shading of size 2 × 2 is considered for both the TCT connection and SDS is considered as shown in Fig. 9 and Fig. 10 respectively.

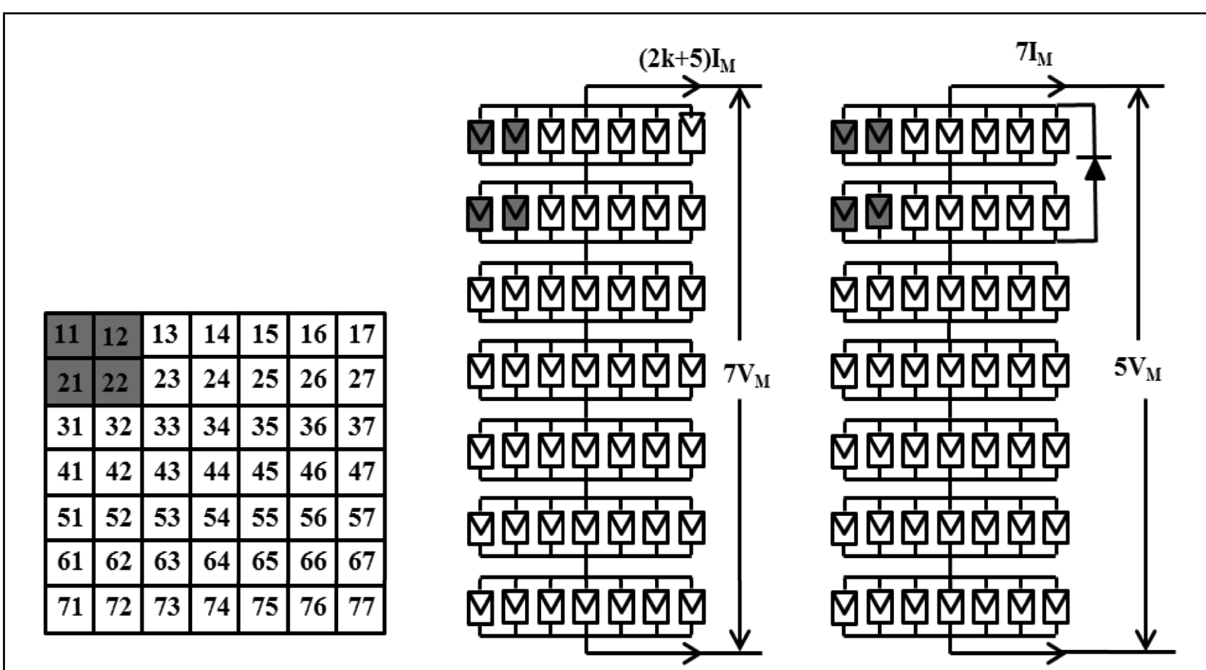
The mismatch loss can be specified from the equation

$$\text{Mismatch Loss} = P_T - P_G \tag{2}$$

where, P_T is the total maximum power generated by each module of a PV array under given irradiance and temperature condition and P_G is the actual power generated by the same PV array under given irradiance and temperature. At an irradiance of I, the current produced by each module is given by

$$I_{Module} = \frac{I}{I_O} \times I_M = kI_M \tag{3}$$

where, I_M is the current generated by the module at standard irradiance of $I_o = 1000\ \text{W/m}^2$ and $k = I/I_o$. So, the current produced by each module depends on the irradiance falling on the module. More the irradiance received by the module, more will be the current generation. The voltage across the PV array is given by the sum of voltages of all rows i.e.



(a) (b) (c)

Fig. 9. (a) Shading of a 7 × 7 PV array with TCT connection. (b) Array without bypassing the shaded rows. (c) Array with bypassing the shaded rows.

$$V_a = \sum_{i=1}^{a} \mathrm{V_{ij}} \tag{4}$$

where, $\mathrm{V_a}$ is the voltage across PV array and $\mathrm{V_{ij}}$ is the voltage of modules at ith row. The current across each node according to Kirchhoff's Current Law is expressed as

$$I_a = \sum_{j=1}^{b} \left(I_{ij} - I_{(i+1)j} \right) = 0, \mathrm{for\ \ i} = 1, 2, \ldots, (\mathrm{a}-1). \tag{5}$$

The power generated by a 7 × 7 TCT configuration array is explained below with 2 × 2 shading condition.

In the first row, two modules i.e. 11 and 12 are shaded and the remaining five i.e. 13, 14, 15, 16 and 17 are unshaded as shown in Fig. 8 (a). So, the current generated in this row is

$$I_{R1} = k_{11}I_M + k_{12}I_M + k_{13}I_M + k_{14}I_M + k_{15}I_M + k_{16}I_M + k_{17}I_M \tag{6}$$

where $k_{11} = I_{11}/I_O = k(<1)$ and I_{11} is the irradiance received by the module numbered 11.

$$I_{R1} = 2kI_M + 5I_M = (2k+5)I_M \tag{7}$$

Similarly, two modules in the second row i.e. 21 and 22 are shaded and the other five i.e. 23, 24, 25, 26 and 27 are unshaded. So,

$$I_{R2} = 2kI_M + 5I_M = (2k+5)I_M \tag{8}$$

The current generation of the remaining four rows is same as every module in the row receives 1000 W/m^2. So,

$$I_{R3} = I_{R4} = I_{R5} = I_{R6} = I_{R7} = 7I_M \tag{9}$$

The typical shading of a 7 × 7 PV array with TCT configuration is shown in Fig. 9 (a) and the same array without bypassing the shaded modules is shown in Fig. 9 (b). The array is represented as series connection of seven parallel modules. As the unshaded modules are forced to deliver the current proportional to shaded modules due to series connection current limitation so, array current is limited to$(2k+5)I_M$. The voltage of the array $V_a = 7V_M$ by neglecting the small variations in voltage across each row. So, the power is

$$P_G = I_a \times V_a = ((2k+5)I_M) \times (7V_M) = 7(2k+5)I_M V_M \tag{10}$$

The PV array with shaded modules is bypassed as shown in Fig. 9 (c). Here, two groups are bypassed out of seven groups connected in series as these two groups have average irradiance less than that of other five groups. So, the current flowing from the array is $\mathrm{I_a} = 7\mathrm{I_m}$.

The array voltage $V_a = 5V_M + 2V_d$where, V_d is the voltage across diode which is neglected as$V_d << V_a$. The power generated by PV array after bypassing the shaded modules is

$$P_G = I_a \times V_a = (7I_M) \times (5V_M) = 35V_M I_M \tag{11}$$

Similarly, same shading pattern is applied to the SDS array and its shading dispersion shown in Fig. 10 (a). Since the connection of the array does not change, the current and voltage of the array remain same as in TCT connection.

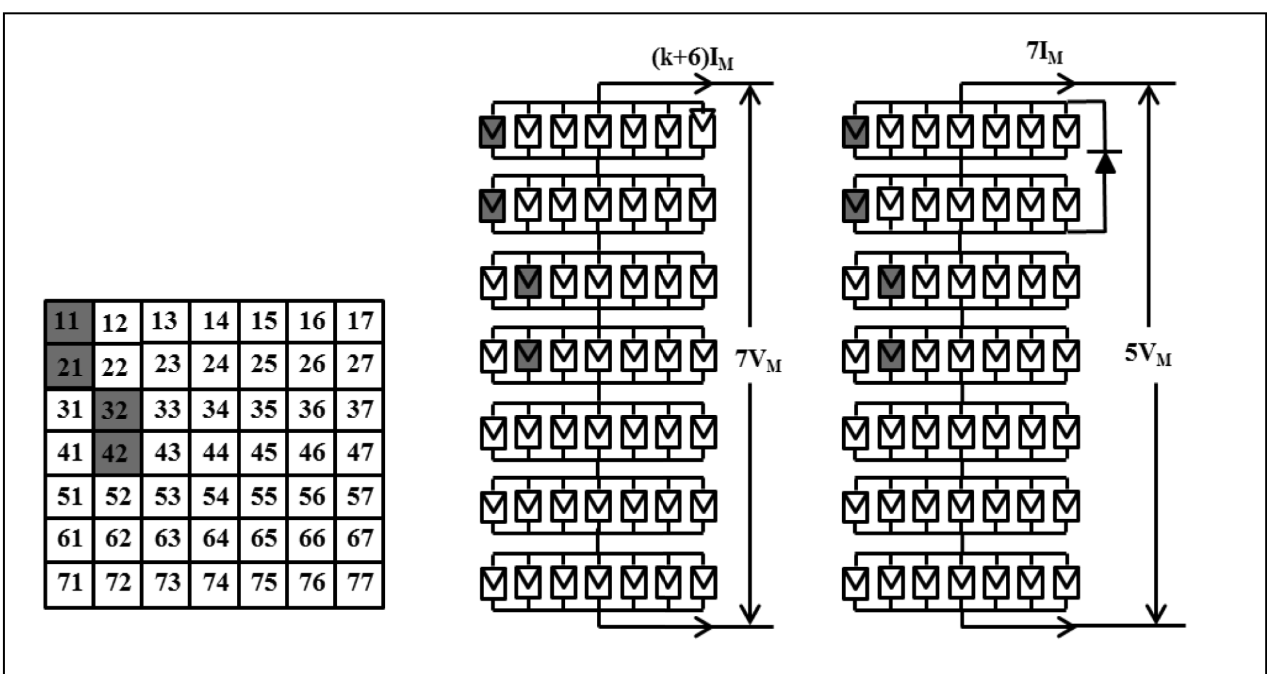
The current generated from row 1, 2, 3, 4 is

$$I_{R1} = I_{R2} = I_{R3} = I_{R4} = kI_M + 6I_M = (k+6)I_M \tag{12}$$

And the current generated from row 5, 6, 7 is

$$I_{R5} = I_{R6} = I_{R7} = 7I_M \tag{13}$$

The array without bypassing the shaded modules is shown in Fig. 10 (b). The array current of this connection is relatively higher than that of TCT connection and is limited to $(k+6)I_M$ due to



(a) (b) (c)

Fig. 10. Shade dispersion in SDS configuration. (b) Array without bypassing the shaded rows. (c) Array with bypassing the shaded rows.

distribution of four shaded modules in four different groups.

So, the power produced by the array without bypassing the shaded modules [Fig. 10 (b)] is given by

$$P_G = I_a \times V_a = ((k+6)I_M) \times (7V_M) = 7(k+6)I_M V_M \tag{14}$$

The power produced by the array with bypassing the shaded modules [Fig. 10 (c)] is given by

Table 1
SPV Module specification AT STC i.e. 1000 W/m^2, 25 °C.

Parameters	Rating
Rated Peak Power(P_{max})	50 W
Voltage at MPP (V_{mp})	17.47 V
Current at MPP (I_{mp})	2.862 A
Open Circuit Voltage(V_{oc})	21.5 V
Short Circuit Current(I_{sc})	3.10 A

$$P_G = I_a \times V_a = (7I_M) \times (3V_M) = 21 I_M V_M \tag{15}$$

In general, when the power from the unshaded modules is greater than the net power from the entire array with reduced current under shading (due to series current limitation), bypassing of shaded modules occurs. But, practically this condition is limited. So, for comparison, power generated without bypassing the shaded row in considered.

The sum of maximum powers generated by individual module is given by

$$P_T = 45 V_M I_M + 4k I_M V_M \tag{16}$$

The mismatch loss in case of TCT connection from (10) and (16) is given by

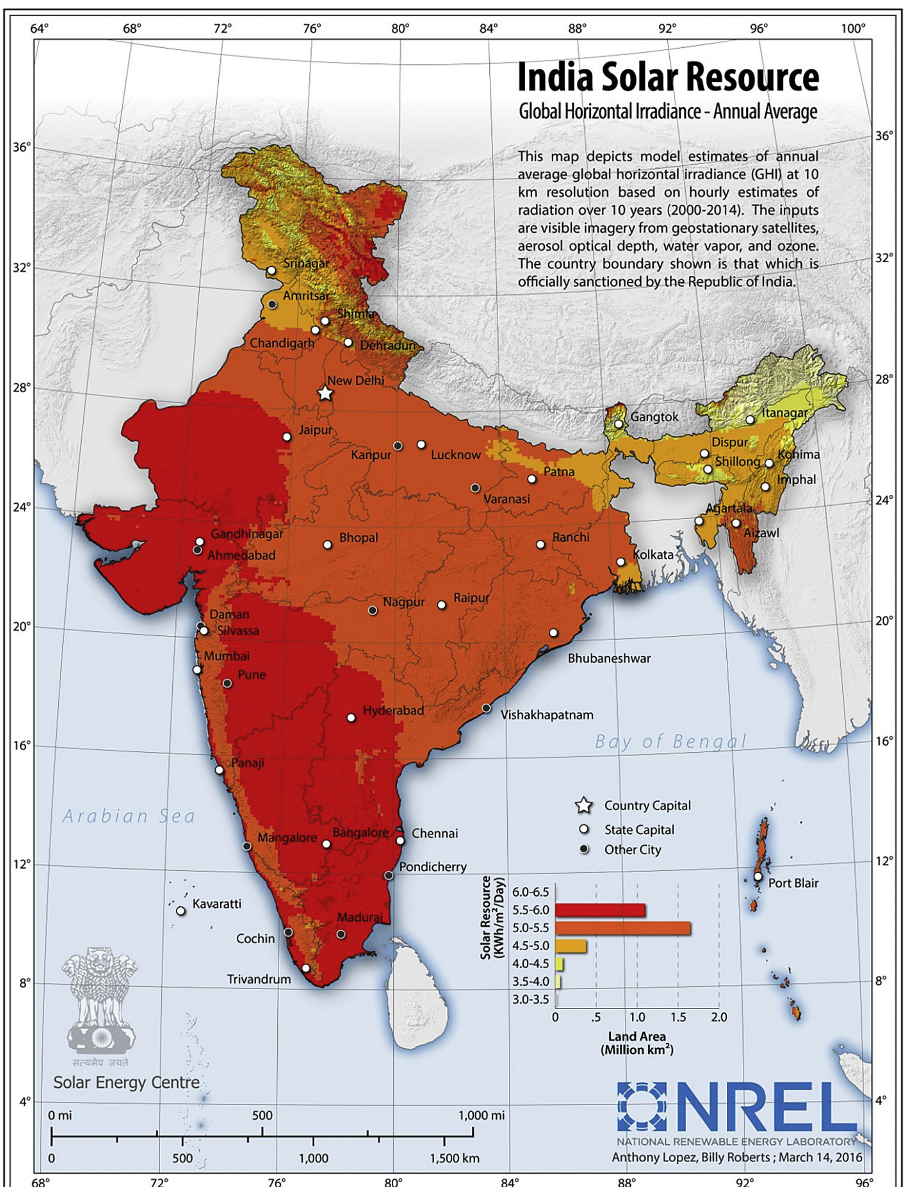
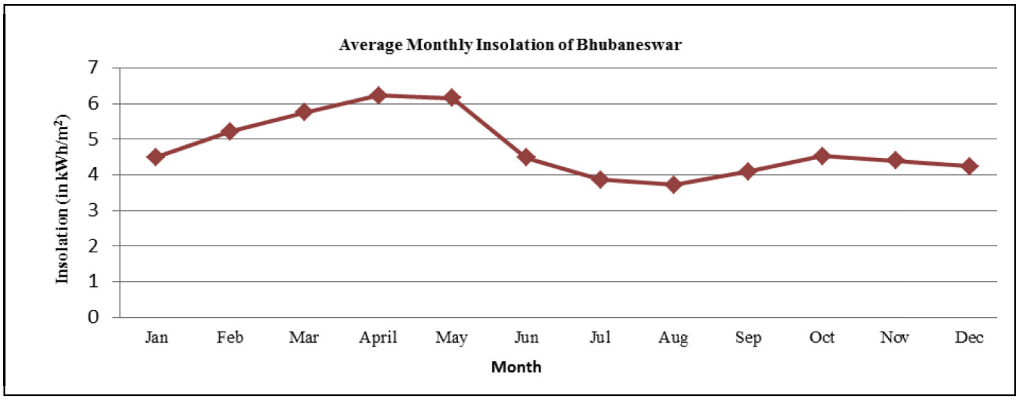
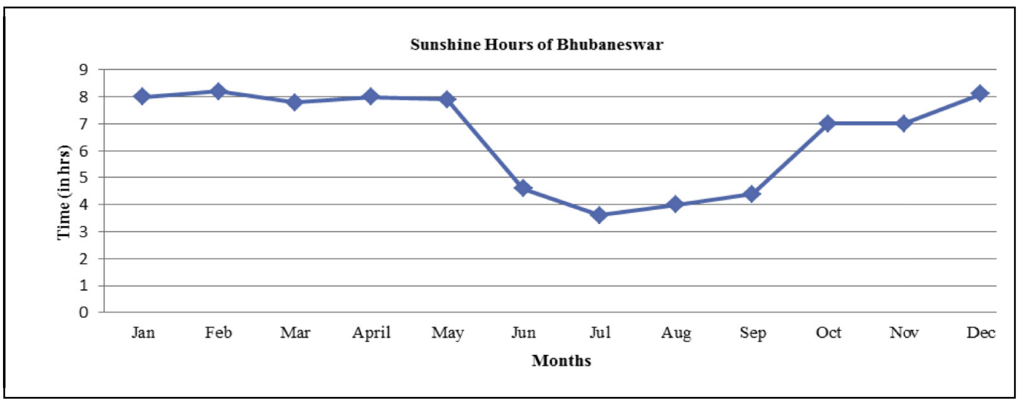


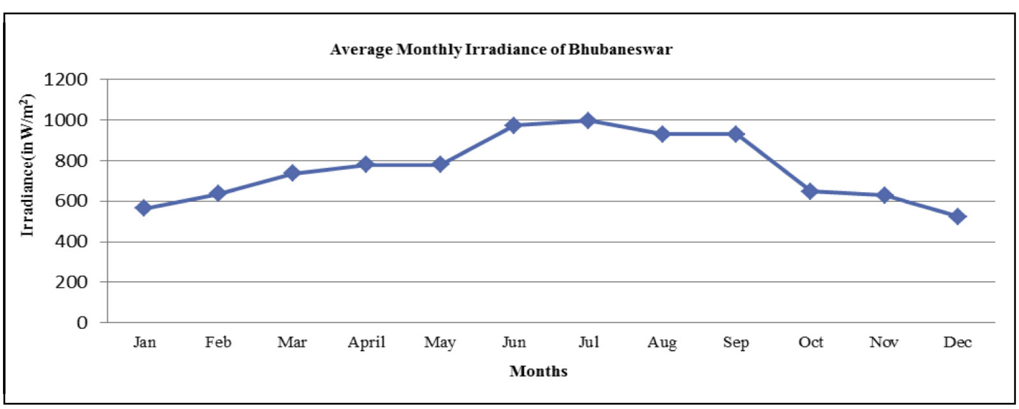
Fig. 11. Average Solar Insolation data of different cities of India (2016) [27].



(a)

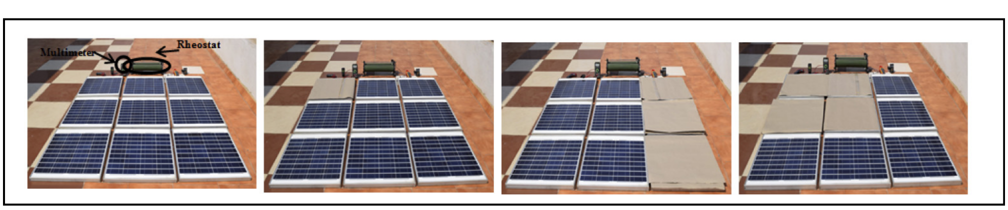


(b)



(c)

Fig. 12. (a) Average monthly Insolation of Bhubaneswar. (b) Average monthly Sunshine of Bhubaneswar. (c) Average monthly Irradiance of Bhubaneswar.



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

Fig. 13. Experimental setup of different types of connection for 3 × 3 SPV array with different shading patterns. (a) Unshaded. (b) One Module Shading. (c) Long Narrow Shading. (d) Short Wide Shading.

$$\mathrm{Mismatch\,Loss} = P_T - P_G = ((45 I_M V_M + 4k I_M V_M) - (7(2k+5) I_M V_M)) = 10(1-k) I_M V_M \tag{17}$$

Similarly, mismatch loss in case of SDS from (14) and (16) is given by

$$\mathrm{Mismatch\,Loss} = P_T - P_G = ((45 I_M V_M + 4k I_M V_M) - (7(k+6) I_M V_M)) = 3(1-k) I_M V_M \tag{18}$$

So, mismatch loss is less in the Shade Dispersion Scheme (SDS) as compared to TCT connection and hence it is proved that during shading, if the modules are rearranged according to the SDS algorithm then, the mismatch loss can be minimized.

6. Results and discussions

The connection schemes are evaluated in MATLAB. The solar module specification at STC considered for experiment is shown in Table 1.

The four interconnection schemes i.e. Series-Parallel (SP), Bridge Linked (BL), Total Cross Tied (TCT) and Shadow Dispersion Scheme (SDS) are compared at different shading patterns for both 3 × 3 SPV array and 7 × 7 SPV array under different irradiance using simulation and practical data. The SPV array under various shading conditions with and without bypass diodes are tested using simulation. The PV curve with and without bypass diodes under various shading conditions for both 3 × 3 and 7 × 7 SPV arrays are presented. The irradiance of unshaded PV modules is kept at 800 W/m^2 and shaded PV modules are kept at 100 W/m^2. The location of Global Maximum Power Point (GMPP) and Local Maximum Power Point (LMPP) in the PV curve of SPV array with and without bypass diodes has been found out using simulation.

Table 2
Power output and loss of different connections during One Module Shading condition.

Connection Type	Power Output (in Watt)	Power Loss (in Watt)	Power Loss (in %)
SP	234.96	121.54	34.10
BL	242.10	114.39	32.08
TCT	258.15	98.35	27.58
SDS	261.00	95.49	26.78

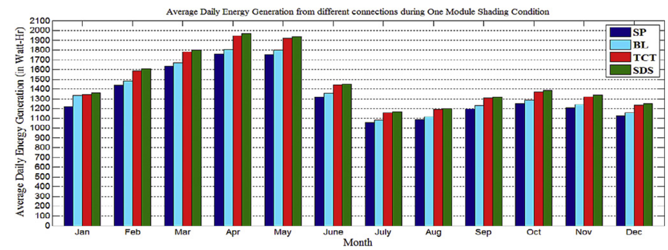


Fig. 15. Average daily energy yield from different connections of 3 × 3 SPV array during One Module Shading condition for different months of a year.

Table 3
Power output and loss of different connections during Long Narrow Shading condition.

Connection Type	Power Output (in Watt)	Power Loss (in Watt)	Power Loss (in %)
SP	227.9	128.50	36.04
BL	228.92	127.57	35.78
TCT	231.3	125.20	35.11
SDS	235.46	121.04	34.02

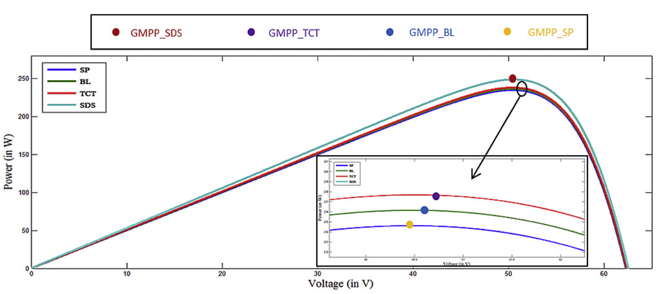


Fig. 16. Location of GMPP in PV characteristics of 3 × 3 SPV array having SP, BL. TCT and SDS interconnections during Long Narrow shading condition.

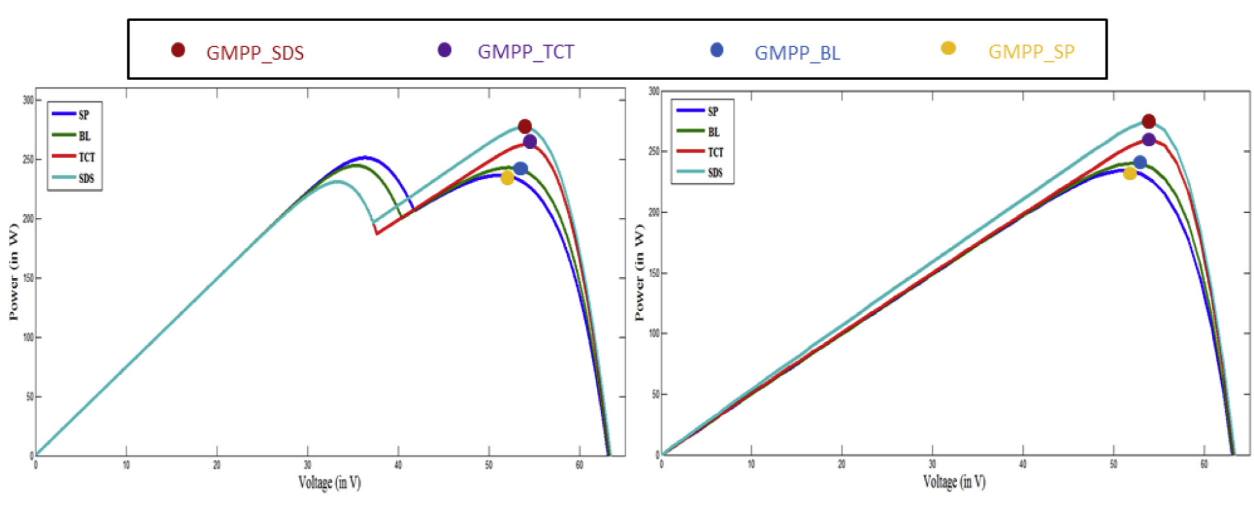


Fig. 14. Location of GMPP in PV characteristics of 3 × 3 SPV array having SP, BL. TCT and SDS interconnections during One Module shading condition. (a) With Bypass diodes. (b) Without Bypass diodes.

A prototype setup in field condition is done using nine 50 Watt SPV modules for 3 × 3 SPV array and forty nine 50 Watt SPV modules for 7 × 7 SPV array to validate the result obtained in simulation. The benefit of using a constant light source for irradiance is that, it produces a constant irradiance. But, the SPV modules never receive a constant irradiance under natural condition. So, to validate these connections under natural condition, the SPV modules receive a natural irradiance measured by Solar Power Meter. The average solar insolation at different places of India [27] is shown in Fig. 11. The experiment was conducted on the roof of the Renewable Lab, E block, SOA University, Bhubaneswar for a year so as to calculate the annual yield of these connections with different shading patterns and irradiance. The average insolation, irradiance and sunshine hours for different months of Bhubaneswar are shown in Fig. 12 (a), (b) and (c) respectively. The average insolation of Bhubaneswar is within 5–5.5 kWh/m^2/day. Bhubaneswar receives highest insolation during the month of April and lowest insolation during the month of August. This implies that the energy yield is maximum during April and minimum during August. The

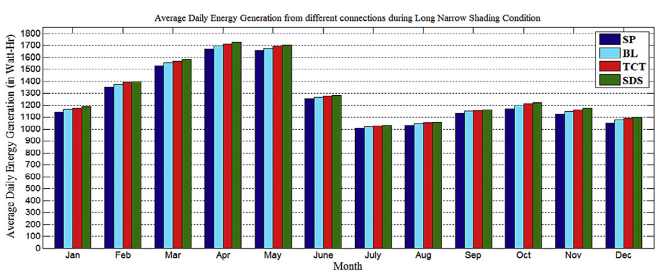


Fig. 17. Average daily energy yield from different connections of 3 × 3 SPV array during Long Narrow Shading condition for different months of a year.

Table 4
Power output and loss of different connections during Short Wide Shading condition.

Connection Type	Power Output (in Watt)	Power Loss (in Watt)	Power Loss (in %)
SP	110.21	246.3	69.08
BL	111.4	245.14	68.76
TCT	114.91	241.6	67.77
SDS	138.83	222.67	64.22

modules are kept horizontally with respect to the ground throughout the year and hence the energy yield is calculated for 3 × 3 and 7 × 7 SPV array with different types of shading patterns. Experimental results are also presented under various shading conditions at irradiance of 800 W/m^2.

6.1. 3 × 3 SPV array

The prototype setup for 3 × 3 SPV array is shown in Fig. 13. The experiment is carried out for different months of year with different shading conditions for all the connections i.e. SP, BL, TCT and SDS for comparison. During normal operating (unshaded) condition as shown in Fig. 13 (a), the array delivers a maximum power output of 359.8 Watt in simulation and 356.5 Watt in field condition at 800 W/m^2. The slight variation in simulation and experimental results is due to difference in temperature, wire loss, cells mismatch and slight irradiance variation during the time of performing experiment. Different types of shadings namely One Module Shading, Long Narrow Shading and Short Wide Shadings are applied to SPV array as shown in Fig. 13 (b), (c) and (d) respectively to validate that SDS yields more power during shading than that of conventional interconnections i.e. SP, BL and TCT.

6.1.1. One module shading

During one module shading condition, one module of the SPV array i.e. module numbered as 11 gets shaded as shown in Fig. 7 (a) that leads to minimization of power generation to 65–70% having a loss of 30–35%. The experimental results for power generation and loss of SP, BL, TCT and SDS at 800 W/m^2 during this type of shading

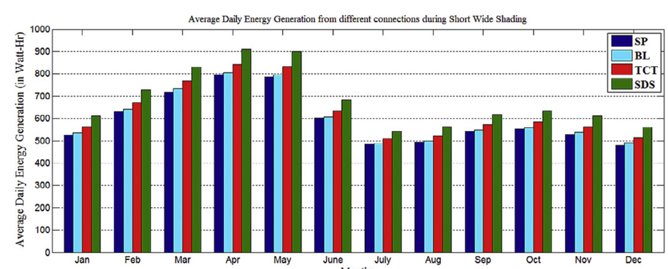
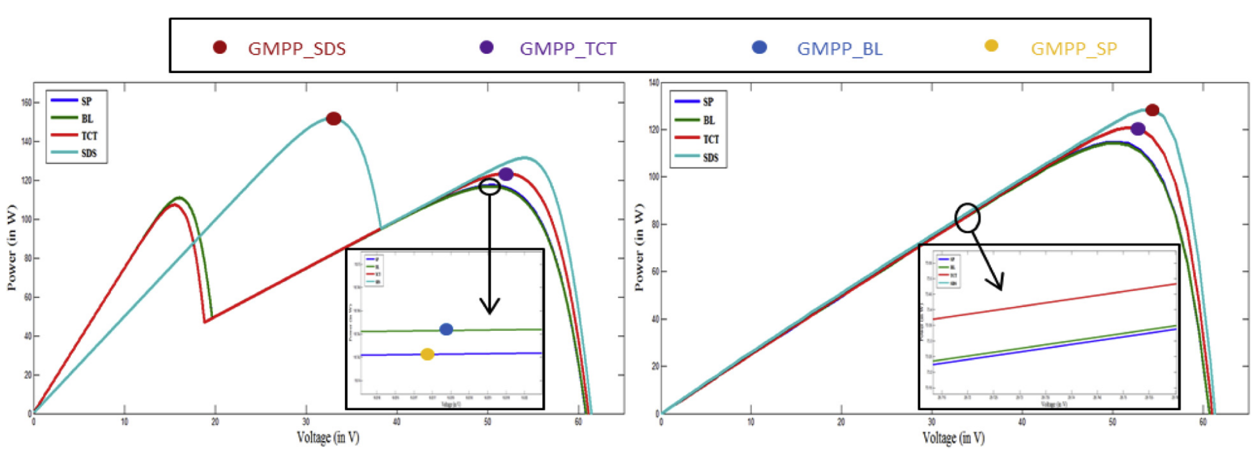


Fig. 19. Average daily energy yield from different connections of 3 × 3 SPV array during Short Wide Shading condition for different months of a year.



(a) (b)

Fig. 18. Location of GMPP in PV characteristics of 3 × 3 SPV array having SP, BL. TCT and SDS interconnections during Short Wide shading condition. (a) With Bypass diodes. (b) Without Bypass diodes.

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

Fig. 20. Experimental setup of different connection types for 7 × 7 SPV array with different shading patterns. (a) Unshaded. (b) Short wide shading. (c) Long narrow shading. (d) Center shading. (e) L-shaped shading. (f) One module shading.

conditions is given in Table 2.

SP shows highest power loss of 34.10% whereas BL show 32.08% power loss. TCT and SDS have a comparatively less power loss of 27.58% and 26.78% respectively. SDS has a slight less power loss as compared to TCT and hence proved to be more efficient during this type of shading.

The PV curve of SP, BL, TCT and SDS under this type of shading condition with and without bypass diodes has been shown in Fig. 14 (a) and (b) respectively. It has been found that when bypass diodes are connected in parallel with the shaded PV modules, the PV curve of array got more than one maximum power points known as local maximum power point (LMPP) and global maximum power point (GMPP). In both the cases i.e. with and without bypass diodes, the location of GMPP of SDS connection is found to be in maximum as compared to SP, BL and TCT.

The annual experimental result for power generation from SP, BL, TCT and SDS during one module shading condition has been shown in Fig. 15. It has been found that SP generated the lowest power whereas SDS generated the maximum power output throughout the year.

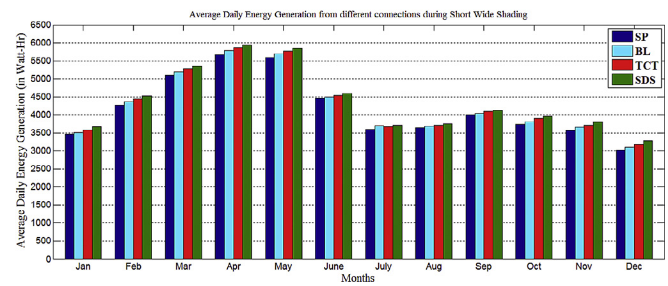


Fig. 22. Average daily energy yield from different 7 × 7 SPV connections during Short Wide Shading condition for different months of a year.

6.1.2. Long narrow shading

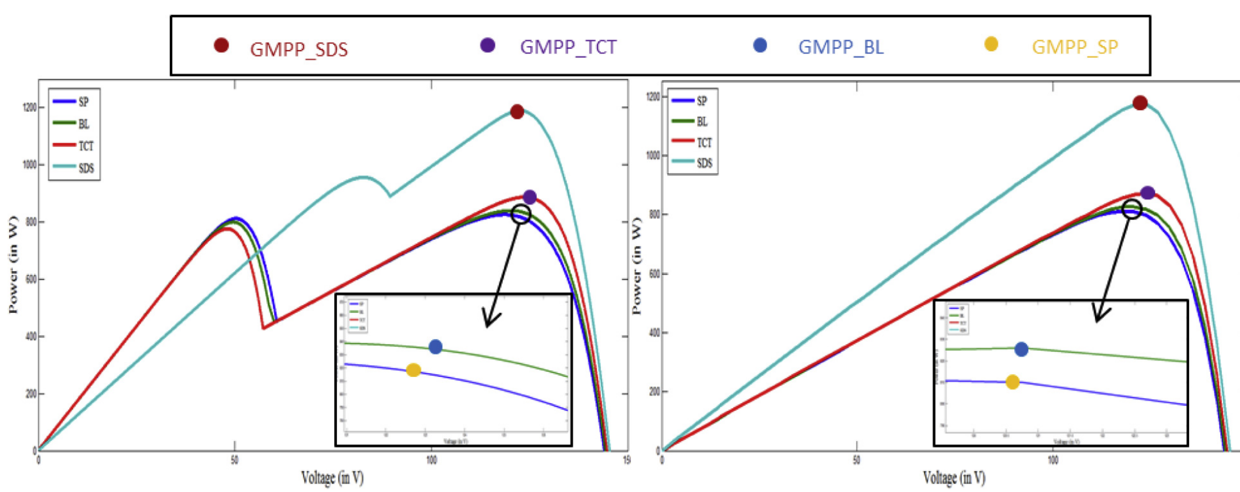
During long narrow shading condition, modules belonging to last column of SPV array i.e. modules numbered as 13, 23 and 33 are

Table 5
Power output and loss of different connections during Short Wide Shading condition.

Connection Type	Power Output (in Watt)	Power Loss (in Watt)	Power Loss (in %)
SP	735.96	1210	62.18
BL	747.89	1198.07	61.56
TCT	756.90	1189.06	61.10
SDS	970.20	975.80	48.42

Table 6
Power output and loss of different 7 × 7 SPV connections during Long Narrow Shading condition.

Connection Type	Power Output (in Watt)	Power Loss (in Watt)	Power Loss (in %)
SP	1026.68	919.28	47.24
BL	1036.03	909.93	46.75
TCT	1040.14	905.82	46.54
SDS	1044.66	901.30	46.31



(a) (b)

Fig. 21. Location of GMPP in PV characteristics of 7 × 7 SPV array having SP, BL. TCT and SDS interconnections during Short Wide shading condition. (a) With Bypass diodes. (b) Without Bypass diodes.

shaded as shown in Fig. 7 (b). During this type of shading, the power generation is less than 60–65% having a loss of 35–40%.

Table 3 represents the experimental results for power generation and loss of SP, BL, TCT and SDS at 800 W/m^2 during this type of shading conditions. During this type of shading, TCT shows a better performance as compared to SP and BL. The performance of SDS (235.46 W) is slightly higher than that of TCT (231.3 W) which can be implemented in larger SPV array to reduce huge losses due to shading. The PV curve showing the GMPP of all the interconnections has been shown in Fig. 16. As one string of the PV array is subjected to shading so, the current output from the string decreases and same amount of current will flow through all the modules of the string. So, there will be only one GMPP in the PV characteristics with and without bypass diodes.

The average daily energy yield of SP, BL, TCT and SDS for different months under long narrow shading condition is shown in Fig. 17. SDS shows a better performance during this type of shading as compared to SP, BL and TCT throughout the year.

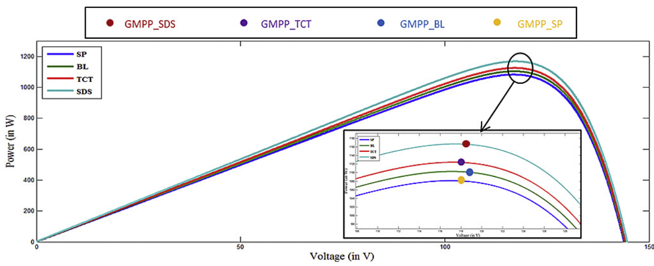


Fig. 23. Location of GMPP in PV characteristics of 7 × 7 SPV array having SP, BL. TCT and SDS interconnections during Long Narrow shading condition.

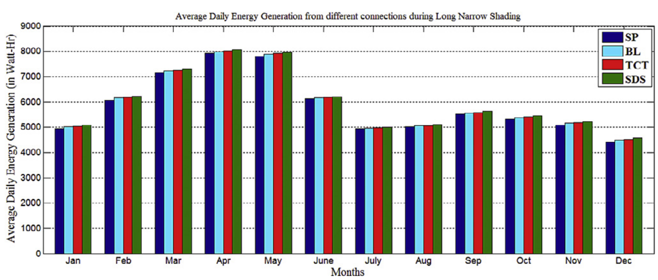


Fig. 24. Average daily energy yield from different 7 × 7 SPV connections during Long Narrow Shading condition for different months of a year.

Table 7
Power output and loss of different 7 × 7 SPV connections during Central Shading condition.

Connection Type	Power Output (in Watt)	Power Loss (in Watt)	Power Loss (in %)
SP	1039.50	906.46	46.58
BL	1067.90	878.06	45.12
TCT	1080.60	865.36	44.46
SDS	1287.53	658.43	44.11

6.1.3. Short wide shading

During short wide shading, four modules belonging to two rows of the SPV array i.e. module numbered 11, 12, 21 and 22 are shaded as shown in Fig. 7 (c). Shading two rows of SPV array affects the power generation from other modules from all the connection schemes. Modules (11, 32 and 21, 22) are physically present in same row but electrically connected to three different rows as shown in Fig. 5 (c). This type of shading has an adverse effect on the power generation from SPV array as it delivers 30% of the output power generated. It is found that SP, BL and TCT faced a huge power loss during this type of shading. Loss in SDS is very low as compared to the conventional interconnection schemes i.e. SP, BL and TCT. The power generation and loss of each connection from experimental setup is illustrated in Table 4.

The power generated by SDS (138.83 W) is quite effective with a reduced loss percentage (64.22%) as compared to SP (110.21 W, 69.08%), BL (111.4 W, 68.76%) and TCT (114.91 W, 67.66%). This type of shading affects the shaded PV modules of different strings by lowering the current output. So, there will be more than one maximum point in the PV curve. The PV curve showing the GMPP of all the interconnections with and without Bypass diodes has been shown in Fig. 18. It has been found that the GMPP in case of SDS is in maximum as compared to other conventional interconnection schemes.

The average daily yields of these interconnections for different months during this type of shading are shown in Fig. 19. Throughout the year, SDS yielded maximum energy and proved to be best connection scheme to mitigate the losses due to short wide shading.

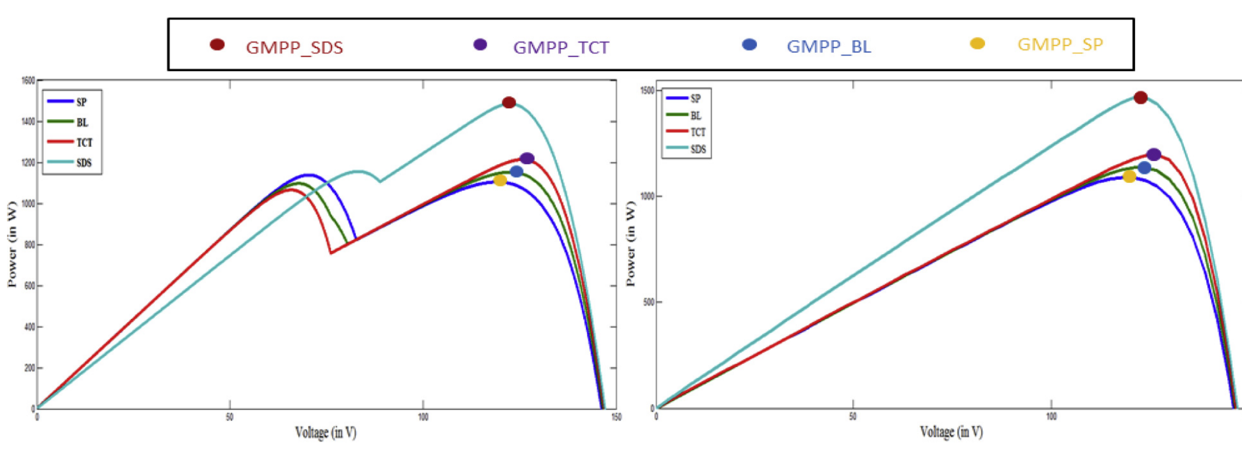


Fig. 25. Location of GMPP in PV characteristics of 7 × 7 SPV array having SP, BL. TCT and SDS interconnections during Central shading condition. (a) With Bypass diodes. (b) Without Bypass diodes.

6.2. 7 × 7 SPV array

The prototype setup for 7 × 7 SPV array is shown in Fig. 20. The Experiment is performed with different shading patterns throughout the year for all the four connections namely SP, BL, TCT and SDS.

During unshaded condition as shown in Fig. 8 (a), the array generates a maximum power output of 1958.9 Watt (1.95 KW) in simulation and 1945.96 Watt (1.94 KW) during experiment at 800 W/m^2. The minor inconsistency between experimental and simulation result is due to temperature difference, other factors such as wire loss and mismatch in cells and slight irradiance variation during the time of performing experiment. Different shading patterns such as Short Wide, Long Narrow, Center, L-Shaped and One Modules have been applied to SPV array to validate that SDS yields maximum power than SP, BL and TCT is shown in Fig. 8 (b), (c), (d), (e) and (f) respectively.

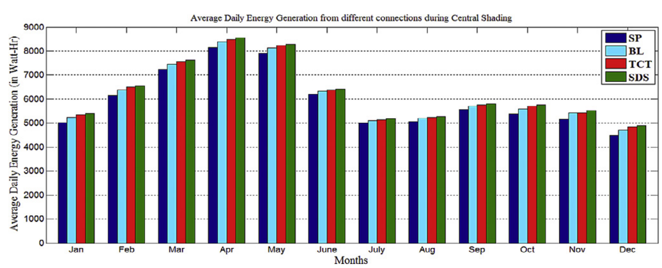


Fig. 26. Average daily energy yield from different 7 × 7 SPV connections during Central Shading condition for different months of a year.

Table 8
Power output and loss of different 7 × 7 SPV connections during L-Shaped Shading condition.

Connection Type	Power Output (in Watt)	Power Loss (in Watt)	Power Loss (in %)
SP	734.77	1211.19	62.24
BL	761.53	1184.43	60.86
TCT	777.66	1168.30	60.03
SDS	1091.53	854.43	43.32

6.2.1. Short wide shading

During Short wide shading of 7 × 7 SPV, the modules belongs to first four rows and columns are being subjected to shading as shown in Fig. 8 (b). This type of shading is considered as malicious for SPV arrays as it lower the power generation to 35–40% with a loss of 60–65%. The experimental results for power generation and loss of SP, BL, TCT and SDS at 800 W/m^2 has been given in Table 5. The simulation PV curve showing the GMPP of all the interconnections with and without Bypass diodes has been shown in Fig. 21. It has been found that the GMPP in case of SDS is in maximum as compared to other conventional interconnection schemes. This indicated SDS will produce maximum power during short wide shading conditions.

It is found that SP faced a huge power loss (62.18%) during this type of shading. SDS has a comparatively less power loss (48.42%). So, SDS can be implemented to reduce power loss due to short wide shadings. The average daily energy generation by all the connections in different months of a year is shown in Fig. 22 that shows SDS yielded more power as compared to SP, BL and TCT throughout the year.

6.2.2. Long narrow shading

During Long Narrow shading, modules belongs to last three columns are shaded as shown in Fig. 8 (c) that leads to decrease in power output to 50–55% with a loss of 45–50%. The experimental results of power generation and loss at 800 W/m^2 is given in Table 6.

SP (47.24%) has highest power loss during this type of shading followed by BL (46.75%) and TCT (46.54%). SDS (46.31%) has comparatively low power loss than others.

The PV curve showing the GMPP of all the interconnections has been shown in Fig. 23. As three string of the PV array are subjected to shading so, the current output from the string decreases and same amount of current will flow through all the modules of the strings. So, there will be only one GMPP in the PV characteristics with and without bypass diodes. The average daily energy generation in different months of a year by SP, BL, TCT and SDS has been shown in Fig. 24 that shows SDS yields slight maximum energy as compared to other connection schemes.

6.2.3. Central shading

In this, the center of the 7 × 7 SPV array is shaded that consists

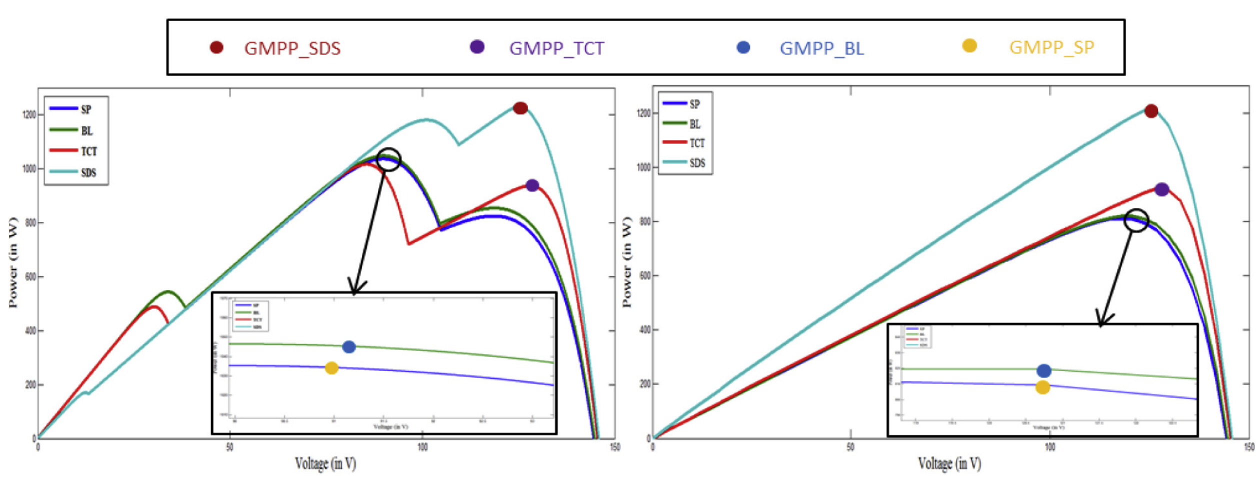


Fig. 27. Location of GMPP in PV characteristics of 7 × 7 SPV array having SP, BL. TCT and SDS interconnections during Central shading condition. (a) With Bypass diodes. (b) Without Bypass diodes.

of nine SPV modules as shown in Fig. 8 (d) leads to a reduced power loss to 50–55% with a power loss of 45–50%. The experimental results for different types of connections under this type of shading pattern at 800 W/m^2 is given in Table 7. SDS show better results with minimum loss during this type of shading pattern. SDS has a slight less power loss as compared to TCT configuration. Fig. 25 represents the simulation PV curve showing the GMPP of all the interconnections with and without Bypass diodes during central shading condition. It has been found that the GMPP in case of SDS is in maximum as compared to other conventional interconnection schemes. The daily average energy yield by all the connection in different months of a year is shown in Fig. 26. SDS generated maximum energy as compared to other connections during central shading throughout the year.

6.2.4. L-shaped shading

The SPV modules are shaded in L shaped pattern as shown in Fig. 8 (e) for comparison of the four interconnection schemes which leads to decreased power output to 35–40% having a power loss of 60–65%. The experimental results of different interconnection schemes during this type of shading at 800 W/m^2 is given in Table 8.

SP has a maximum power loss of 62.24% as compared to BL (60.86%) and TCT (60.03%). SDS has a lowest power loss as compared to other configurations i.e. 43.32%. The simulation PV curve representing the GMPP of all the interconnections with and without Bypass diodes during central shading condition has been shown in Fig. 27. It has been found that the GMPP in case of SDS is in maximum as compared to other conventional interconnection schemes. The average daily energy yield in different months of a year from different interconnection schemes under this type of shading is shown in Fig. 28. SDS is proved to be the best configuration for this type of shading as it yield maximum power throughout the year.

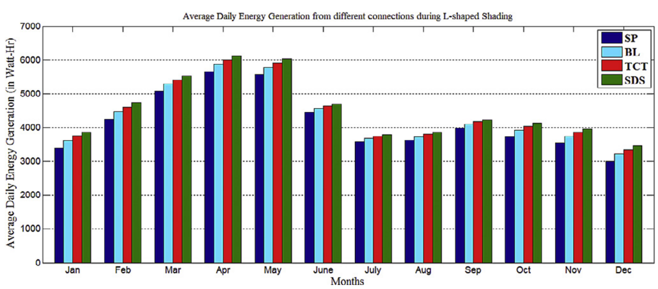


Fig. 28. Average daily energy yield from different 7 × 7 SPV connections during L-shaped Shading condition for different months of a year.

Table 9
Power output and loss of different 7 × 7 SPV connections during One Module Shading condition.

Connection Type	Power Output (in Watt)	Power Loss (in Watt)	Power Loss (in %)
SP	1644.36	301.40	15.48
BL	1689.84	256.12	13.16
TCT	1721.55	224.41	11.53
SDS	1746.33	199.63	10.25

6.2.5. One module shading

During One module shading, one module of the SPV array is subjected to shading that result in reduction in power output to 85–90% with a power loss of around 10–15%. Table 9 represents the experimental results during this type of shading at 800 W/m^2.

SP encountered maximum power loss of 15.48% followed by BL (13.16%) and TCT (11.53%). SDS has minimum power loss of 10.25% and is found to be optimal configuration during this type of shading. The simulation PV curve showing the GMPP of all the interconnections with and without Bypass diodes has been shown in Fig. 29. It has been found that GMPP of SDS is in maximum as compared to SP, BL and TCT.

The daily average energy generation in different months of a year from different connection schemes during this shading pattern is shown in Fig. 30. SDS yields the maximum power throughout the year as compared to SP, BL and TCT.

So, from the above results, it is make a sense that SDS produced maximum power under various shading conditions as compared to the other conventional interconnection topologies such as SP, BL and TCT. An optimal interconnection scheme is the one that can enhance maximum power during shading conditions. SDS can be implemented as an optimal interconnection to enhance the power generation during various types of possible shading in field condition. It has also been studied that interconnection schemes are

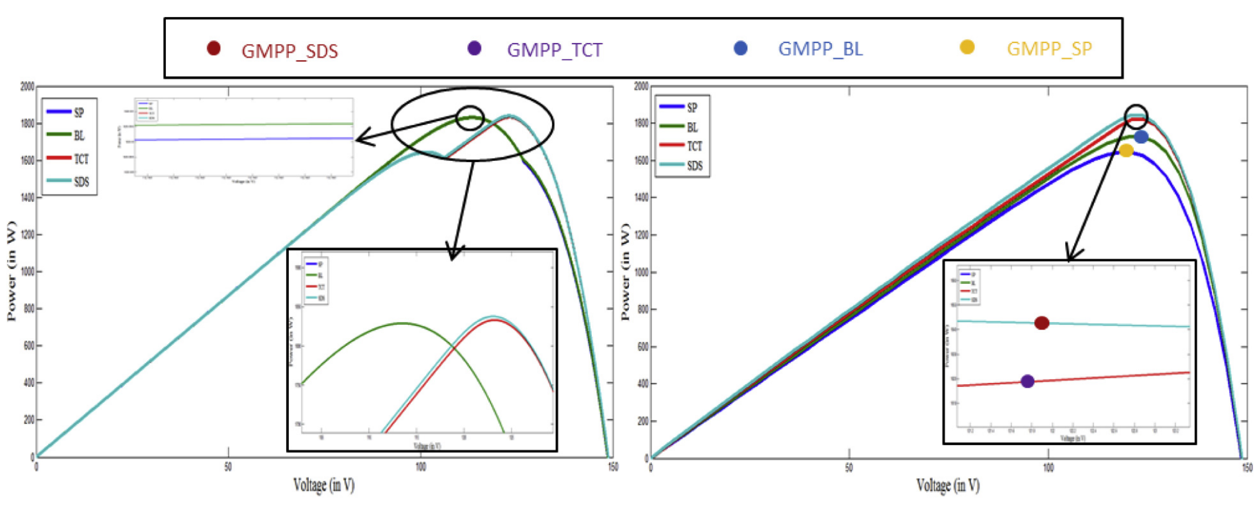


Fig. 29. Location of GMPP in PV characteristics of 7 × 7 SPV array having SP, BL. TCT and SDS interconnections during One Module shading condition. (a) With Bypass diodes. (b) Without Bypass diodes.

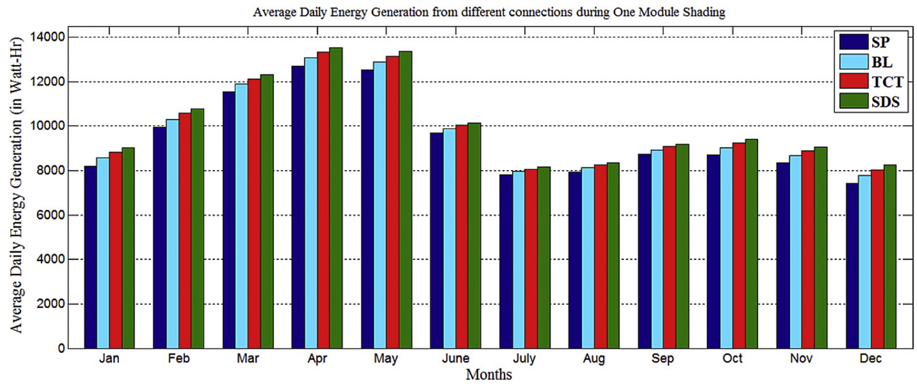


Fig. 30. Average daily energy yield from different 7 × 7 SPV connections during One module Shading condition for different months of a year.

meant to provide alternative paths for current produced by the unshaded modules within the array. SDS provides different path for current produced by unshaded modules to avoid the flow of current from shaded modules.

7. Conclusion

In view of the above, mentioned results are the indication of the fact that SDS involves minimum power losses. SDS has also yielded maximum power as compared to the other conventional interconnection schemes such as Series-Parallel (SP), Bridge Linked (BL) and Total Cross Tied (TCT) throughout the year with different shading patterns. Our results of 7 × 7 SPV array further indicates that, the array with SDS configuration have maximum power generation and minimum power losses among all the interconnections. SDS interconnection may be applied to array up to size of 7 × 7 and then for subarrays. Several subarrays can be integrated to constitute an array which is ambient to be the most efficient SPV array.

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