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Optimal Interconnections among Partial Shaded Array Modules of T-C-T Solar Photovoltaic Array Configuration

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Abstract*:* In this paper, the Series-Parallel (SP) and Total-Cross-Tied (T-C-T) type of conventional solar photovoltaic (SPV) array configurations or topologies are considered for modeling and comparative analysis and the parameters mainly maximum power of array, shading losses, number of interconnections or ties between array SPV modules are compared with the proposed optimal configuration under six partial shading scenarios and one un shaded case. The proposed optimal topology, optimize the number of ties required among PV modules and improves the output power of SPV array as compare to TCT configuration and also minimizes the shading power losses. These optimal interconnections are based on the location of number of shaded modules in the SPV Array. For this study, the Vikram Solar ELDORA 270 PV modules are used for modeling and simulation of SP, TCT and proposed optimal topologies in MATLAB/ Simulink software.

Index Terms*:* PV module and array power, Interconnections, Shading losses, Irradiances, Partial shading cases.

1. Introduction

Solar Photovoltaic modules consists of cells which converts sunlight into electricity. The efficiency of PV modules approximately less than 20% under full irradiance of 1000W/m^2, it will be reduced due to partial shading effect with variable irradiances up to 1000 W/m^2. The performance of SPV system depends on irradiance, soiling, shading, degradation, operating temperature etc., due to shading effect [1-2] the power output of array reduced to a lower value as compared to full irradiance condition of 1000 w/m^2 it causes power losses. Due to shading local hot spots developed in the modules it leads to permanent damage of SPV modules [3]. To minimize this losses under shading conditions, many techniques such as puzzle pattern based arrangements, repositioning of modules, Sudoku puzzle based arrays etc., has been developed without altering the electrical connections of modules in SPV arrays but the length of interconnections wires in between modules are increases it results more line losses [4].

The available conventional configurations such as Bridge Linked (B-L), Series-Parallel(S-P), Hill-Climbing (H-C), Total-Cross-Tied (TCT) connection types. As compared to other configurations the TCT connection has minimum mismatch or shading losses under various shading scenarios as presented in different literature research work [5-8]. This paper proposes an optimal interconnections for a 5x5 size TCT SPV system and analyze the performance under six different possible partial shading conditions. As compared to SP and TCT topologies, the proposed optimal technique minimizes the number of interconnections/ ties/wires among modules, reduces the mismatch power losses and increases the power generation from SPV array as compared to S-P configuration [9]. The proposed optimal method creates an alternative path for current distribution between modules under un-shaded and partial shaded conditions with minimum number of interconnections or ties in the solar photovoltaic array. The proposed optimal method reduces the installation cost and wiring time during installation of SPV system and complexity of interconnections among modules as compared to TCT configuration of PV system. In this paper mainly modeling of 5x5 SPV array with SP and TCT configurations are presented and compare the number of ties and global maximum power, power losses with proposed optimal configurations.

In this paper, the mathematical modeling of SPV array and proposed methodology adopted for optimal interconnections, various partial shading cases are presented in section-2 and 3 respectively. Matlab/ Simulink models of SP, TCT and proposed optimal topologies under different shading cases are given in in section-4. The number of ties or interconnections and array power analysis of SP, TCT and proposed topologies presented in section-5.

2. Mathematical Modeling

2.1. Modeling of Solar PV Array

The PV Module has solar cells that converts directly solar irradiance into DC electricity by photovoltaic effect. The PV array consists of number of series connected (N_S) and parallel connected modules (N_P) as shown in figure-1.

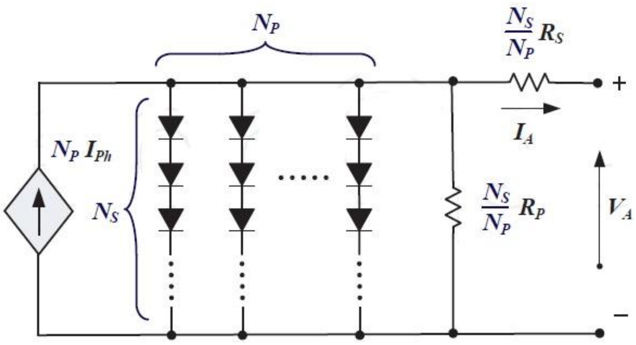

Fig.1. Solar PV Array with N_S x N_P PV modules

The mathematical representation of PV array [10] as given in Equation-(1).

$$\mathbf{I_A = I_{ph}N_P - I_{RS}N_P\left\{\exp\left[\frac{1}{A.V_{TH}}\left(\frac{V_A}{N_S}+\frac{I_A.R_S}{N_P}\right)\right]-1\right\} - \frac{N_P}{R_P}\left(\frac{I_A.R_S}{N_P}\right)} \quad (1)$$

Where I_A and V_A are output current[A] and voltage[V] of array, I_{Ph}: Solar cell photocurrent[A], I_{RS}: Solar cell diode reverse saturation current [A], R_S: series resistance[Ω], R_P: parallel resistance[Ω], A: Ideality factor of P-N junction solar cell diode (value 1-5), V_{Th}: Cell thermal voltage[V] as V_{Th}= k T_C/q, where T_C: Solar cell operating temperature [K], q:Electron charge [1.602e-19 Cb], k: Boltzmann's constant [1.38e-23 J/K].

2.2 Simple 5x5 size photovoltaic system

The 5x5 PV plant has M=5 number of modules connected in one string and N=5 number of parallel connected string as shown in figure-2. The grid integration of solar PV system through power electronics interface devices are not considered in this work, only different interconnection PV topologies are considered for analyzing optimal connections of different configurations.

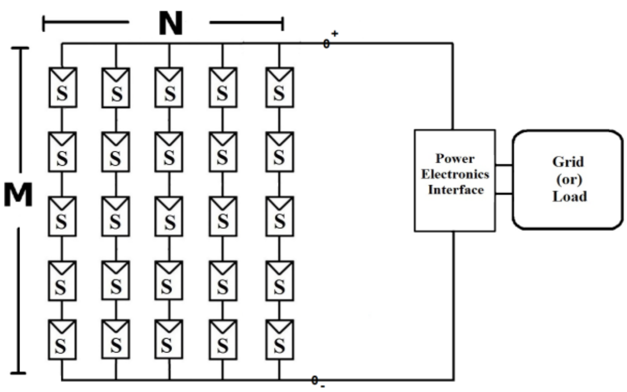

Fig.2. 5 x 5 size SPV Plant

2.3 PV model Parameters:

In this paper, the specifications of Vikram Solar ELDORA 270 PV module are used for the design of different Array configurations as tabulated in Table-1.

Table 1. Specifications of Vikram Solar ELDORA 270 PV module under STC (1000 W/m^2 and 25^{o}C)

Parameters		Values
Maximum Power		270 W
Cells per module	N_{cell}	72
Open circuit voltage	V_{OC}	44 V
Short-circuit current	I_{SC}	8.1A
Voltage at maximum power point	V_{MP}	34.7 V
Current at maximum power point	I_{MP}	7.8A
Temperature coefficient of V_{oc}		-0.3583% / °C
Temperature coefficient of I_{sc}		0.0249% / °C
Light generated current	I_L	8.1924 A
Diode saturation current	I_o	2.4871e-10
Diode ideality factor		0.98223
Shunt resistance	R_{sh}	3126.5623 Ω
Series resistance	R_s	0.52303 Ω

2.4 Solar PV Array Configurations or Topologies:

The main Solar PV array topologies are [11-12],

a. Series connection topologies
b. Parallel connection topologies
c. Series-Parallel (S-P) type of topologies
d. Total-Cross-Tied (T-C-T) type of topologies
e. Bridge-Linked (B-L) type of connection and
f. Honey-Comb (H-C) type of topologies.

The figure-3 shows different SPV array topologies.

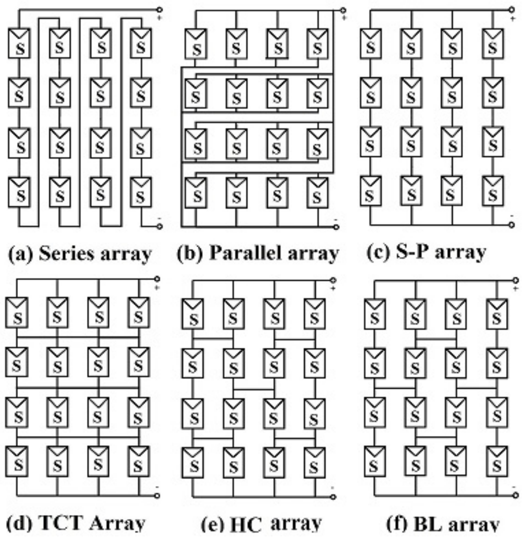

Fig.3. Different solar PV array Configurations

In series (S) connection, all modules are connected and in parallel (P) connection all modules are connected in parallel. In series type high voltages and in parallel type high currents are produced by the array due to this reason, for many PV applications S and P type configurations are not suitable. In this paper mainly SP, TCT connections are considered and compare the performances with new proposed optimal topology.

i. Series(S)–Parallel (P) Configuration

The S-P configuration as shown in figure-3(c). In this topology, PV modules are connected in series known as strings and this strings are connected in parallel to form S-P topology. Figure-3(c) shows the 4x4 size S-P topology with 4 number of series connection modules (strings) and 4 number of strings connected in parallel to form 4x4 SPV array configuration.

ii. Total (T)-Cross(C)-Tied (T) Configuration

The TCT configuration shown in figure-3(d). In this topology, interconnections or ties are added among SPV modules in S-P type of topology to form TCT array connection. The performance of TCT topology has better than S-P topology under shading cases.

iii. Proposed Optimal Configuration

The proposed optimal configuration is formed by minimization of number of interconnections or ties or wires in TCT type SPV array configuration with the help of connection switch (CS) analysis as discussed in section-3.1 among the modules in the SPV array.

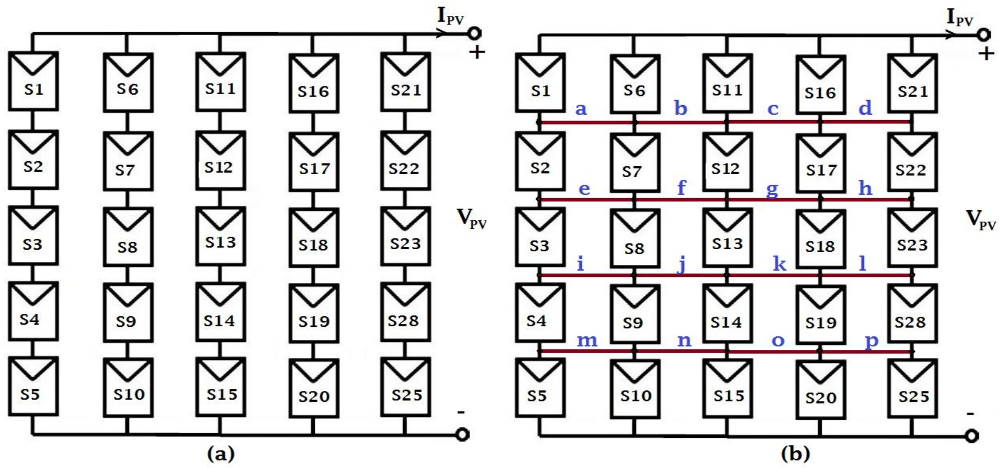

Fig.4. (a) 5x5 Series-Parallel SPV array (b) TCT SPV array with number of interconnections or ties

3. Proposed Optimal Method of SPV Array Configuration

3.1. Methodology for optimal interconnections of PV Array:

The entire PV array is divided into a small 2x2 size sub PV arrays. Let us consider 2x2 sub array of 5x5 SPV array with four modules S1, S2, S3 and S4. In this 2x2 array, depends upon position of number of shaded modules there are seven shaded cases are possible and tabulated these cases in Table-2. For analyzing this 2x2 sub array, proposed a connection switch (CS) method with tie connections between modules in an SPV array.

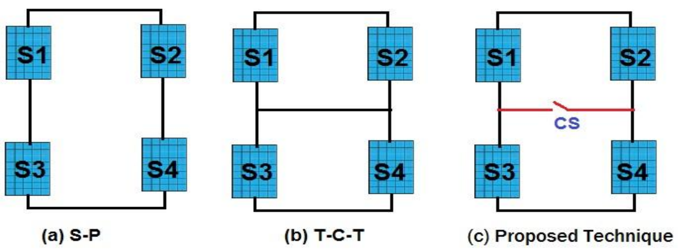

Fig.5. 2x2 SP, TCT and Proposed PV Array Topologies

The connection switch CS=0 means tie/connection is absent and CS=1 means tie is present. The simulation results of global maximum powers for a 2x2 SPV array with connection switch analysis [12] i.e., if connection/ tie is present or absent among the modules under seven possible shading cases for irradiances 700 W/m^2 are tabulated in Table-2. The fig-5 shows the 2x2 size S-P, TCT and proposed optimal topology.

The possible seven cases of a 2x2 array with PV modules S1, S2, S3 and S4 are shown in figure-6[13-14]. In Case-I, all modules in the array receives uniform irradiance of 1000 W/m^2. The maximum power obtained under uniform case with and without tie/connection is equal to 6676W, so in between modules a tie or interconnection not required.

In Case II, shaded moduleS1 receives irradiance of 500 W/m^{2}and remaining three modules receives 1000 W/m^2. The power obtained without tie is less than with tie, so in this case, a tie is required among the modules.

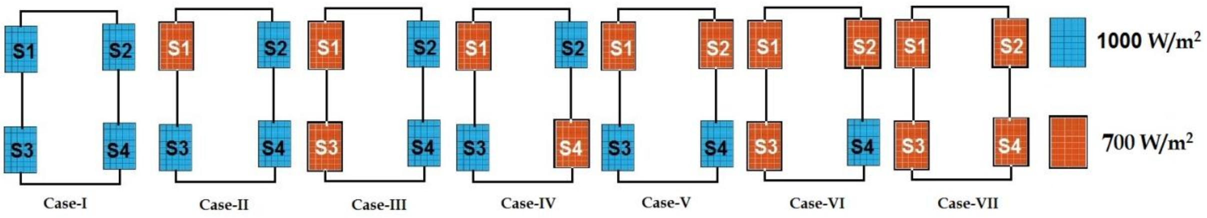

Fig.6. Possible shaded cases for 2x2 PV Array

In Case-III, IV and V: two modules are shaded in vertical position (S1, S3), diagonally (S1, S4) and horizontal position (S1, S2) as shown in figure-4. If two modules are shaded horizontal or vertical position out of four, the output power is same, in this case a tie may be omitted. If the diagonally opposite connected shaded modules are present, a tie among the modules is required to get more maximum power.

In Case VI: modules S1, S2 and S3are shaded and module S4 is un-shaded. The obtained output power of array is more with tie, so that a tie is required in between the modules.

In Case-VII: all four modules are shaded. The obtained maximum power of array with and without tie are equal, so a tie is not required among the modules.

Out of seven possible shading cases, in cases I, III, V and VII only tie is not required due to the maximum power obtained is equal with and without tie and in cases-II, IV, VI, the maximum power output is less without tie so that a tie required in between modules. It is observed that the obtained maximum power from array is depends on position of number of shaded modules. In proposed method, most of the cases a tie is not required and number of interconnections among the modules are reduced in the PV Array. From the Table-2, it is concluded that if one module shaded or two diagonally shaded modules or three module shaded case the tie among the modules in an array is required and for other cases interconnection or tie not necessary in between modules.

Table-2. Maximum power of possible seven cases with irradiance of 700 W/m^2

Case	Shadow type	Maximum Power P_m(W) of shaded modules of irradiance 700 W/m^2		Tie Required (Yes/No)
		CS=0	CS=1	
I	No Shade	1062	1062	No
II	One shaded module	930.2	**948.4**	**Yes**
III	Two shaded modules in Series	908.1	908.1	No
IV	Two diagonally shaded modules	804.3	**908.1**	**Yes**
V	Two shaded modules in Parallel	804.3	804.3	No
VI	Three Shaded module	776.9	**790.9**	**Yes**
VII	All modules are shaded	755.3	755.3	No

3.2 Partial Shading Scenario:

The main reason for Partial shading (PS) is due to changes in tilt angles of modules, shading nearby buildings, clouds, bird litters, falling tree leaves on modules, dust formed on modules because of pollution.

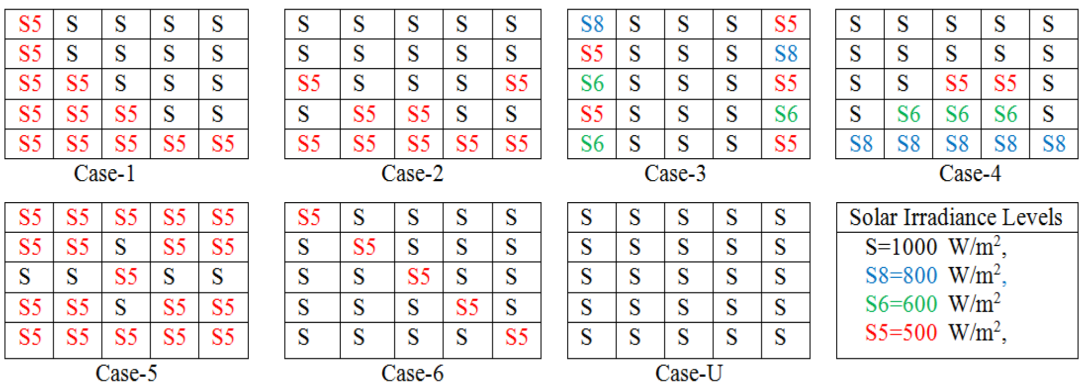

Fig.7. Different partial shading cases considered for simulation

In this work, the effect of partial shading is analyzed for 5x5 size **S**-P, T-C-T and proposed topologies of SPV arrays under six number of shading cases and one un-shaded case (case-U) as received irradiance of 1000 W/m^2. In other cases (case1-6), PV modules are shaded partially with different irradiance levels i.e., less than 1000W/m^2 as shown in figure-7. In un-shaded case (case-U), all modules in the array are received full irradiance of 1000W/m^2.

4. Modeling And Simulation Of SP, T-C-T And Proposed Optimal Configurations

4.1 Modeling of optimal interconnection configuration for shading case-2

In this section, the modeling of 5×5 size solar PV array topologies are presented. For modeling of PV array with shaded case-2 as shown in figure-7, the proposed optimal method explained step by step in figure-8. In the proposed method, the complete 5x5 size SPV array is sub divided into a 2x2 small SPV arrays and analyze the number of interconnections among modules by the proposed connection switch (CS) method as discussed in figure-6. The total number of ties required for case-2 as tabulated in Table-3. Where a, b, c, d, e, f, g, h, i, j, k, l, m, n, o and p are the interconnections or ties among the modules in the 5x5 size SPV array system.

Proposed optimal method: Step by step procedure for shading case-2

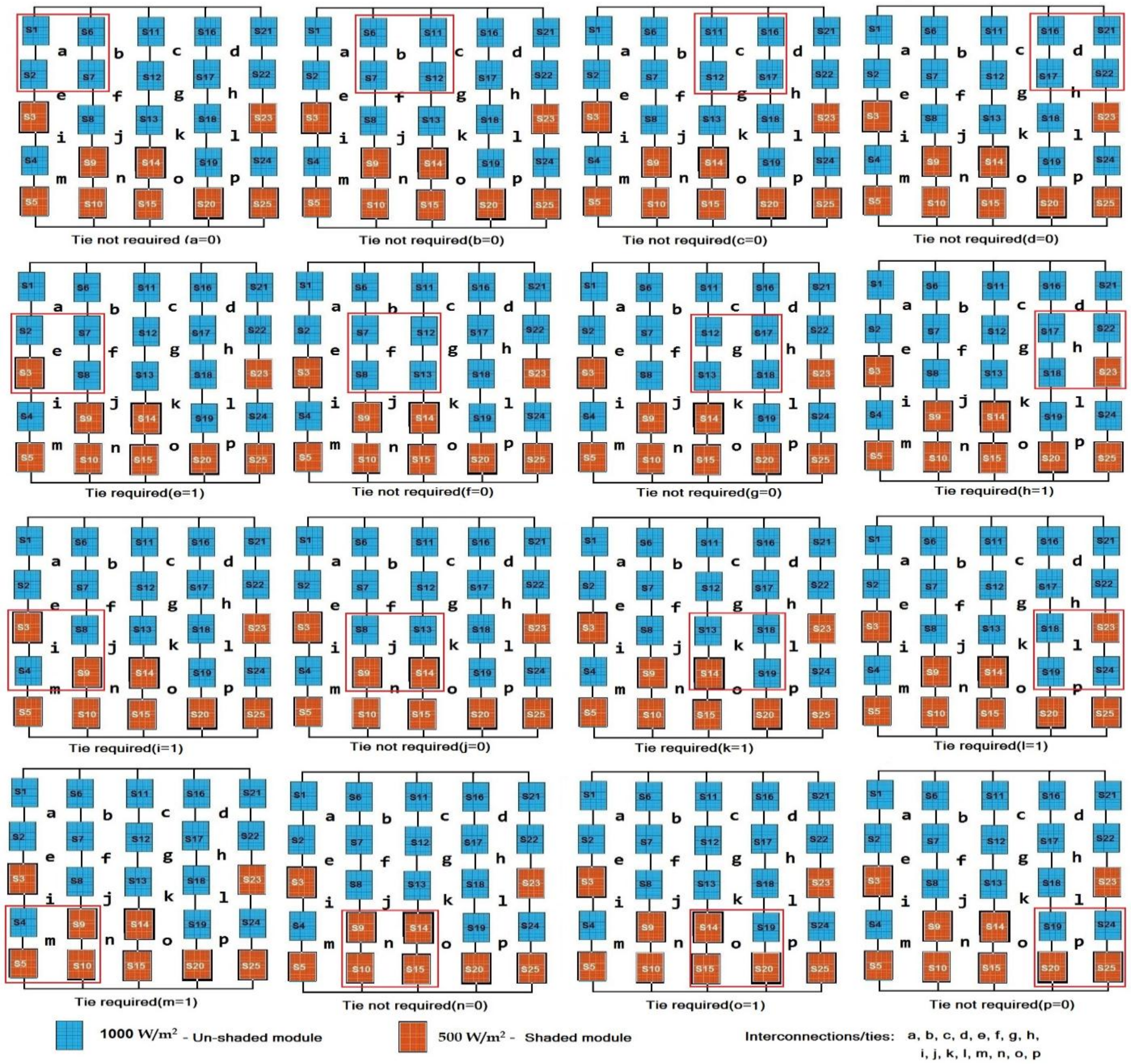

Fig.8. Proposed optimal interconnection analysis for case-2

The proposed optimal method applied for the partial shading case-2 as shown in figure-7.The step by step explanation of required number of interconnections or ties are given in Table-3.

Table-3. Proposed optimal interconnections for case-2 shading

Shaded Modules	Un-shaded Modules	No. of Shaded modules	Tie required(Yes/No)	Optimal Interconnections
-	S1,S2,S6,S7	0	No	a=0
-	S6,S7,S11,S12	0	No	b=0
-	S11,S12,S16,S17	0	No	c =0
-	S16,S17,S21,S22	0	No	d=0
S3	S2,S7,S8	01	Yes	e=1
-	S7,S8,S12,S13	0	No	f=0
-	S12,S13,S17,S18	0	No	g=0
S23	S17,S18,S22	01	Yes	h=1
S3, S9	S4,S8	02	Yes	i=1
S9,S14	S8,S13	02	No	j=0
S14	S13,S18,S19	01	Yes	k=1
S23	S18,S19,S24	01	Yes	l=1
S5,S9,S10	S4	03	Yes	m=1
S9,S10,S14,S15	-	04	No	n=0
S14,S15,S20	S19	03	Yes	o=1
S20,S25	S19,S24	02	No	p=0

Figure-8 shows the interconnections or ties for partial shading case-2. Where a, b, c, d, e, f, g, h, i, j, k, l, m, n, o, and p are interconnections or ties among modules in an array. From the connection switch analysis as discussed previous section 3.1, the tie connections **e, h, i, k, l, m, o** are only required in between modules in an array and other ties a, b, c, d, f, g, j, p are not necessary among modules. The tie connection is present means 1 and tie absent means 0.

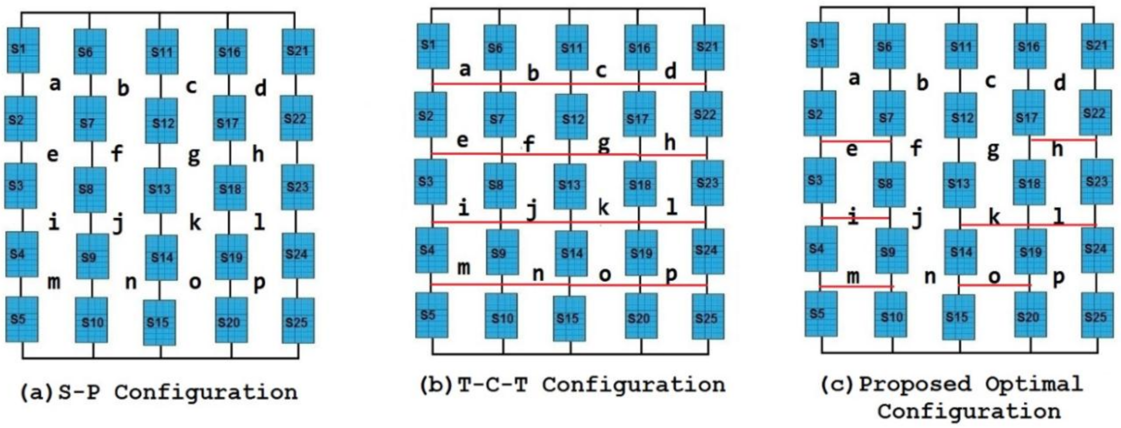

Fig.9. 5x5 size SPV arrays with number of interconnections for case-2

From the 2x2 sub array of 5x5 array analysis explained in the above section 3.1, tie/ interconnections depends up on the number of shaded modules in the array. If the number shaded modules are 4 or 2 or 4 un-shaded modules present in the 2x2 sub array, in this case a tie is not required and the two modules are diagonally shaded or 1 module shaded or 3 shaded modules present, in this case interconnection is required among modules in an SPV array to enhance the output power of array. This concept is applied to partial shaded case-2 and results of number of interconnections/ties are tabulated in Table-4. The optimum number of interconnections among modules of TCT configuration under different proposed shading cases 1-6 and one un-shaded case-U are tabulated in Table-5.

Table-4. Optimal interconnection results for case-2

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	Ties
SP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TCT	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
Proposed	0	0	0	0	1	0	0	1	1	0	1	1	1	0	1	0	07

Table-5. Optimal interconnection results for different cases

Ties / Cases	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	Total Ties
U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	1	1	0	0	0	1	1	0	0	0	1	0	05
2	0	0	0	0	1	0	0	1	1	0	1	1	1	0	1	0	07
3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	1	0	1	1	1	0	0	1	0	0	1	06
5	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	08
6	1	1	0	0	1	1	1	0	0	1	1	1	0	0	1	1	10

4.2 Simulation of SP, T-C-T and Proposed SPV array configurations

The 5x5 size (5 strings and each string as 5 modules) SP, TCT and proposed optimal SPV array configurations with six different shading cases and one uniform irradiance case-U are simulated in Matlab/simulink environment. In this SPV array total 25 PV modules are used and 72 PV cells are connected in series in each module. Every PV module in the string and every string in the array are protected by the anti-parallel bypass diodes and series connected blocking diodes respectively. The specifications of Vikram Solar ELDORA 270 PV module used in simulation are given in Table-1. The simulation models of 5x5 size S-P, TCT and proposed optimal configuration are shown in figures- 10, 11 and 12 respectively.

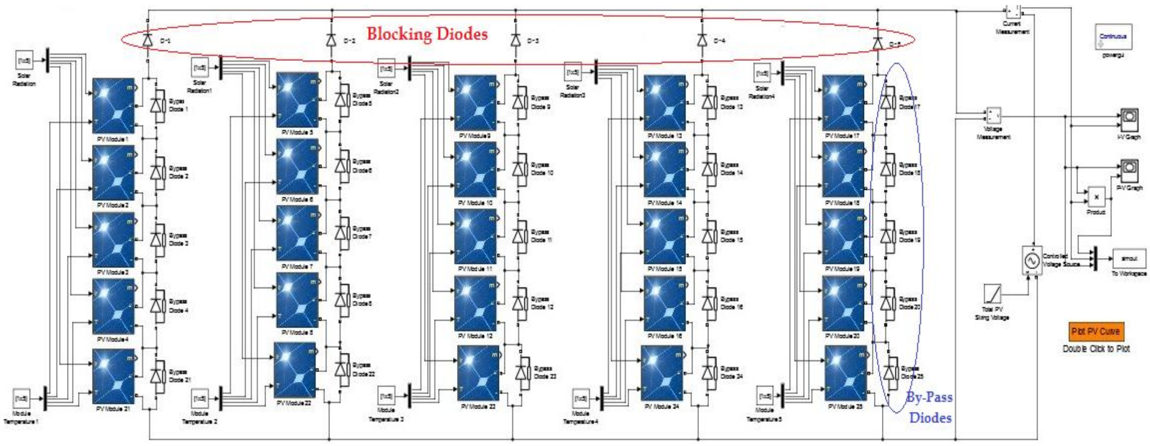

Fig.10. 5x5 Series-Parallel SPV Array simulink model for Case-2

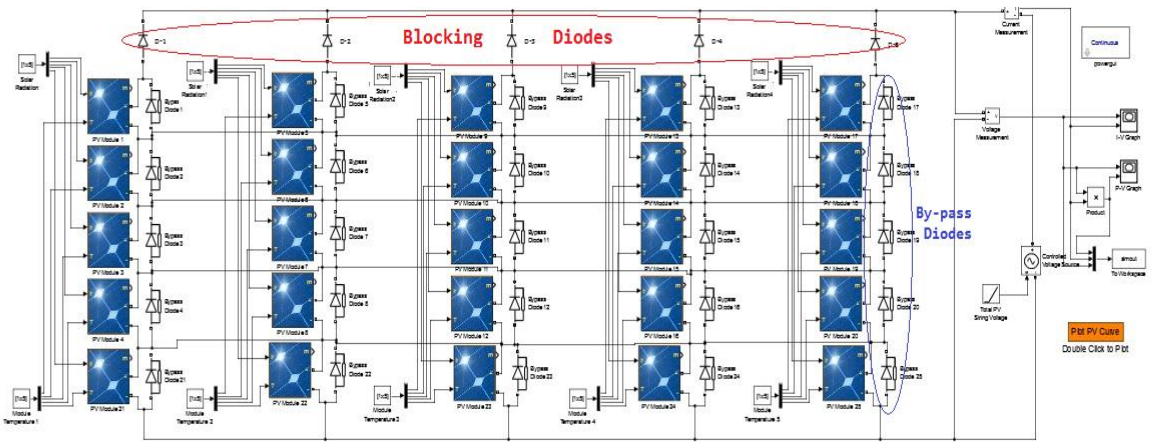

Fig.11. 5x5 Total-Cross-Tied SPV Array simulink model for Case-2

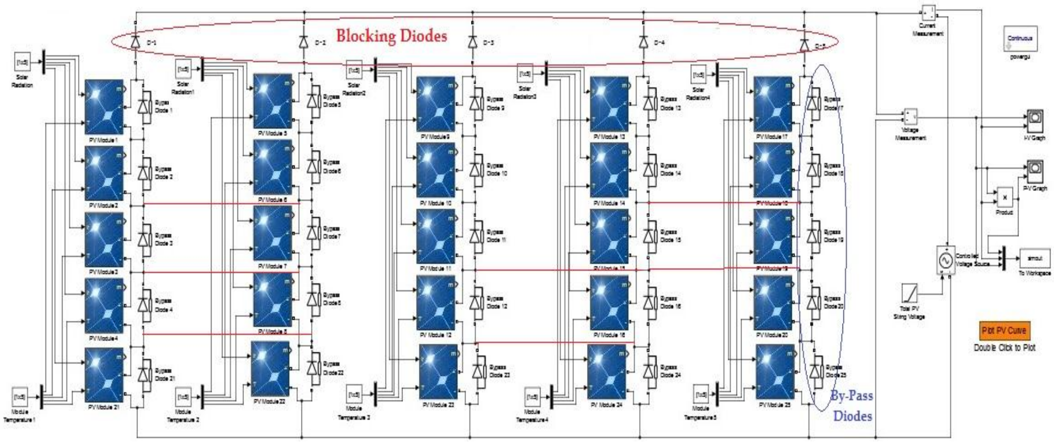

Fig.12. 5x5 Proposed optimal SPV array simulink model for Case-2

5. Results and Discussion

The performance of SP, T-C-T and Proposed optimal array configurations are compared with mismatch losses, array power and number of ties under six different shading cases (cases-1 to 6) and one un-shaded case (case-U) with irradiance of 1000W/m^2. Mismatch power loss of SPV array is given as,

$$P_{mpl} = \frac{P_{mu} - P_{mpsc}}{P_{mu}} x100 \quad (2)$$

Where P_{mu} is the maximum array power at uniform irradiation of 1000 W/m^2 and P_{mpsc} is global maximum power at different partial shading cases.

The output P-V characteristics of SP, TCT and Proposed optimal configurations under six different shading and one uniform irradiance un-shaded case-U are shown in figures-13, 14 and 15 respectively. The number of interconnections between modules in SPV array and obtained global maximum output power of SP, TCT and proposed optimal topologies are shown in figure-16 and 17 respectively. Under un-shaded case-U, the power obtained in SP, TCT and proposed optimal configurations are equal i.e., 6676W and number of ties required for SP and proposed configurations is zero and for TCT type has 16 number of ties required among modules. Under case-3, TCT requires 16 ties and SP, proposed type has no ties required.

Under case-1, proposed topology has only 5 ties and TCT has 16 ties and SP has no ties required.

Under 2,4,5,6 cases proposed topology has 7, 6, 8, 10 ties and for TCT has 16 number of ties required among modules in 5x5 SPV array.

The electrical connections among PV modules a, b, c, d, e, f, g, h, i, j, k, l, m, n, o and p are shown in figure-9. For SP configurations there is no ties are required and in TCT configuration total 16 ties are required among modules and in case of proposed optimal configuration only less number of interconnections or ties required depends upon shading pattern. The number of interconnections, array maximum power and mismatch or shading losses under six different partial shading cases (case-1 to 6) shown in figure-7 are tabulated in Table-6.

The proposed optimal interconnection method is applied to any size of photovoltaic system and improves the array power, requires less number of ties, minimum mismatch losses compared to SP configuration. This optimal method is simple to implement because it doesn't require any switches or sensors and does not required any complex mathematical equations for analyzing this method. The proposed method installation cost of PV system, wiring time for large PV system and minimum cable losses due to less number of ties among the SPV array.

Table-6. Number of Interconnections and Array Power

Case	**Configurations**	**Array Power**	**Mismatch power loss (P_{mpl}) %**	**No. of Ties required**
U	**SP**	6676	0	0
	TCT	6676	0	16
	Proposed	6676	0	0
1	**SP**	3843	42.4	0
	TCT	4064	39.1	16
	Proposed	**3980**	**40.3**	**05**
2	**SP**	3986	40.2	0
	TCT	4498	32.6	16
	Proposed	**4452**	**33.3**	**07**

3	**SP**	5421	18.8	0
	TCT	5586	16.3	16
	Proposed	**5421**	**18.8**	**00**
4	**SP**	4770	28.5	0
	TCT	5480	18.0	16
	Proposed	**5332**	**20.1**	**06**
5	**SP**	3543	47.0	0
	TCT	3651	45.3	16
	Proposed	**3609**	**46.0**	**08**
6	**SP**	5304	20.5	0
	TCT	6022	9.8	16
	Proposed	**6022**	**9.8**	**10**

In this proposed optimal method, the mismatch or partial shading losses given in equation-2 are reduced as compared to series-parallel configuration and number of ties between photovoltaic modules in SPV array are reduced as compared to TCT configuration.

Simulation Results:

The simulation results of 5x5 SPV arrays are:

a. Series(S)-Parallel (P) Configuration:

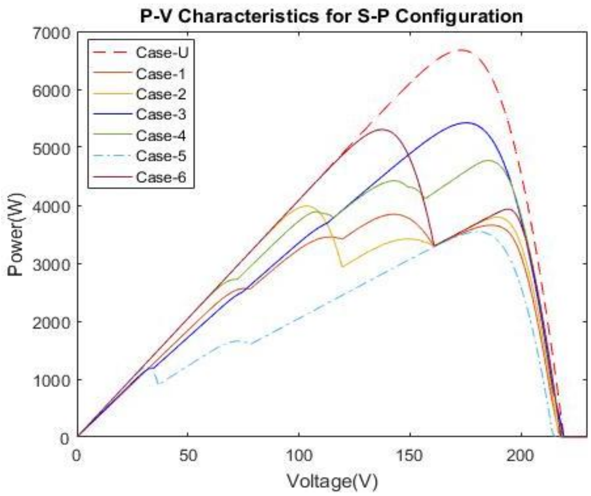

Fig.13. P-V Curves for S- P configuration

b. Total (T)-Cross(C)-Tied (T) Configuration:

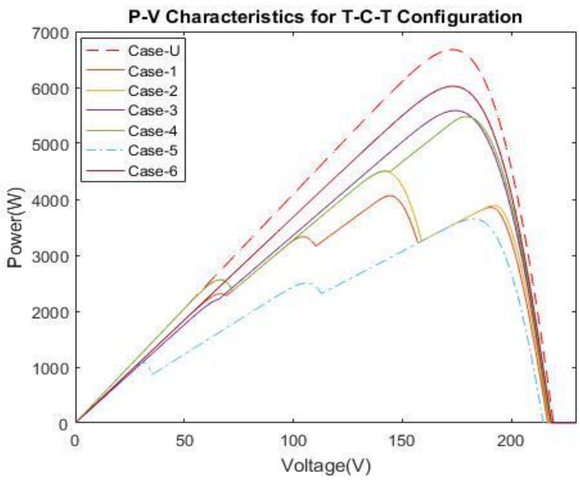

Fig.14. P-V Cures for TCT configuration

c. Proposed optimal configuration:

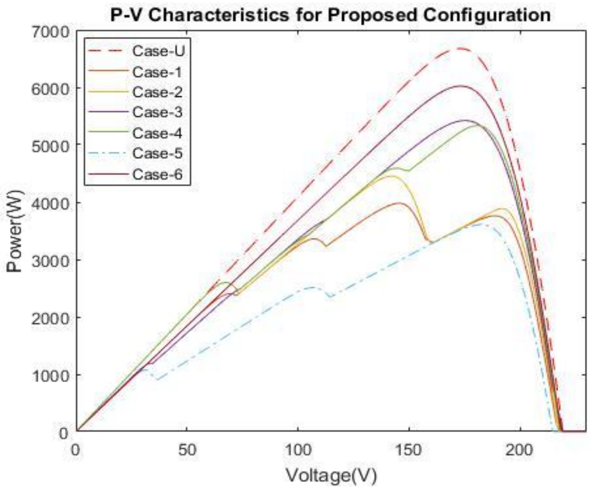

Fig.15. P-V Curves for Proposed optimal configuration

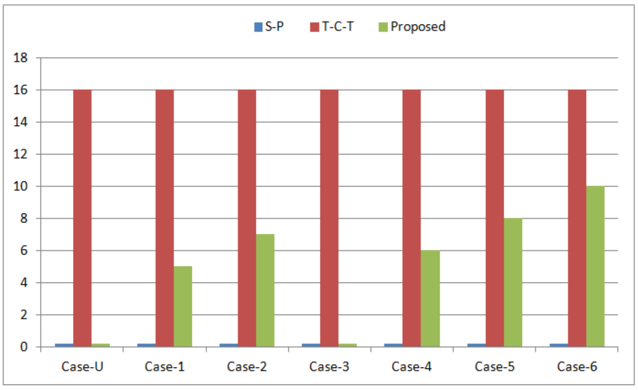

Fig.16. Number of interconnections/ties

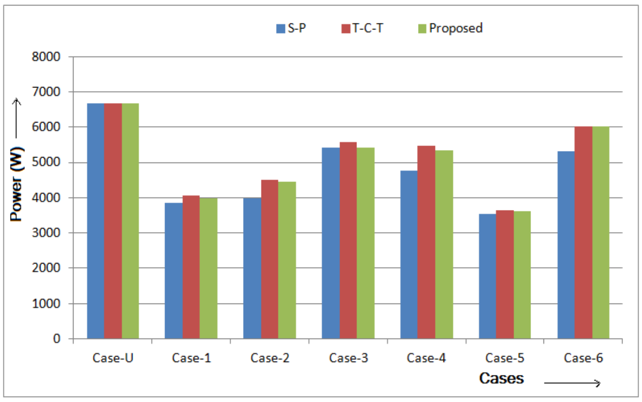

Fig.17. Maximum Power of SP, TCT and Proposed Configurations

7. Conclusions

In this paper the optimal electrical connections among modules in a 2x2 size SPV array with four modules S1, S2, S3, and S4 are studied for possible seven shading cases with optimal connection switch method and proposed an number of optimal interconnections or ties for 5x5 size SPV array. The performance of 5x5 SPV array analyzed under six different partial shading cases. The proposed optimal method improves the array maximum power and reduces the mismatch losses as compared to Series- Parallel configuration and minimize the number of interconnections between modules, time required for wiring, installation cost of photovoltaic system, complexity of modules in an array as compared to TCT array configuration. Finally, the optimal interconnections of TCT configuration are proposed in this study.

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