Performance Analysis of Conventional, Hybrid and Optimal PV Array Configurations of Partially Shaded Modules

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Abstract- In this paper, modeling and performance analysis of conventional configurations are Series-Parallel (SP), Bridge-Linked (BL), Honey-Comb (HC), Total-Cross-Tied(TCT) and proposed hybrid configurations are SP-TCT, BL-TCT, HC-TCT, BL-HC and modified BL(MBL), modified HC(MHC), proposed optimal interconnection type configurations of a 5x5 size solar PV array under ten different partial shading cases it causes shading losses and compare the best configuration with respect to array power, number of interconnections or ties required between shaded modules in the array. The proposed optimal interconnection method reduces the number of ties required between modules and these ties are based on the position of number of shaded modules in the entire solar PV array. For the performance analysis of above 11 configurations, total ten shading cases are considered and compare the result with one un-shaded case-U of an irradiance 1000 Wm². The PV module parameters of Vikram Solar ELDORA 270 are used for modeling of above 11 conventional and proposed PV array configurations and simulate the models in MATLAB/ Simulink software.

Keywords- PV array configurations or topologies, PV module and array power, Irradiances, Partial shaded modules, shading loss, Interconnections or ties.

I. INTRODUCTION

In recent years the power generation at distribution side mainly solar power generation using photovoltaic (PV) systems an alternative to conventional methods of electricity generation with fossil fuels and solar power has pollution free power generation and also possibility of injecting power into the utility power grid for the utilization of power. Due to this solar power generation the effect of global warming due to fossil fuel based generating station reduced[1-3]. Photovoltaic technology converts sunlight directly into electricity, the power generation from photovoltaic cells is simplest and easiest method compare to other renewable sources. The efficiency and array output power reduced due to partial shading on photovoltaic modules. Partial shading occurs due to shadowing of nearby buildings, trees, dust accumulation, passing clouds, bird litters, tree leaves falling on modules, changes in module tilt angles etc., it creates an local hotspots on modules in an array results damage the entire photovoltaic modules. The PV array generated power is much less than that of designed array power due to shading[4] and also local hot spots created in modules it leads to permanent damage of PV cells [5].

Partial shaded modules in an photovoltaic array causes shading losses occurs and reduction in output power. The performance of PV system depends on several factors such as shading, soiling, degradation, bypassed the PV modules, faulty strings, mismatch and operating temperature. The power output of array is reduced due to the effect of partial shading on modules[6]. To minimize this effect, many techniques such as repositioning or rearrangement of modules, Magic-Square pattern and Sudoku puzzle pattern etc., has been developed. In these techniques, based on shadow pattern in the array the optimal position of each module is determined and without changing electrical connections of modules is re-positioned to that optimal location. But, the above methods applicable only for square type arrays in the photovoltaic system and the length of interconnections among modules are increases it leads to more line losses[7-8]. In the proposed method reduces the shading losses, cable losses, installation cost by optimizing the number of ties and increasing the array power output. The conventional configurations are Series(S)-Parallel(P), Total Cross Tied (TCT), Hill-Climbing (H-C) and Bridge Linked (BL) have been proposed in literature for performance and mismatch power loss analysis[7-10,18]. The TCT type has least mismatch or shading power loss as compared to other conventional configurations under various partially shading conditions[9,19]. This paper proposes new modified BL(MBL), modified HC(MHC) configurations and hybrid configurations/ topologies i.e., combination of two conventional configurations such as SP-TCT, HC-TCT, BL-TCT, BL-HC and optimal type of configurations and compare the best topology under ten possible proposed partial shading scenarios of 5x5 size solar photovoltaic system.

This research article starts with the mathematical modeling of photovoltaic array. The 5X5 size photovoltaic system design, module parameters, methodology adopted for proposed method and different partial shading patterns are presented in section-3. In section-4, Modeling and Simulation of SP, BL, HC, MBL, MHC, TCT, SP-TCT, BL-TCT, HC-TCT, BL-HC and proposed optimal configurations under ten different shading cases are presented. The analysis of array power, partial shading losses, mismatch power losses and number of interconnections between modules of above 11 topologies are discussed in section-5. Finally conclusions are given in section-6.

II. Modeling of Photovoltaic Array

The number of series connected solar cells in PV module that directly converts solar radiation into DC current by photovoltaic effect.
The solar photovoltaic array consists of number of modules connected in series and parallel as shown in figure-1.

![Photovoltaic Array with N_s x N_p PV modules](image)

**Figure-1 Photovoltaic Array with N_s x N_p PV modules**

The mathematical representation of PV array composed of number of series connected modules(N_s) and number of parallel connected modules(N_p) [10] shown in Eq. (1).

\[
I_A = I_{phN_P} - I_{RSN_P}\left\{\exp\left[\frac{1}{\alpha V_{oc}} \left(\frac{V_A}{N_s} + \frac{I_{sh}R_S}{N_p}\right)\right] - 1\right\} - \frac{N_p}{R_S}\left(\frac{I_{phN_p}}{N_s}\right)
\]  

(1)

Where I_A and V_A are output current[A] and voltage [V] of array, I_{ph}: Solar cell photocurrent[A], I_{sh}: 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 to 5 ), V_{oc}: Cell thermal voltage[V] as V_{oc}= k T_c/q, where T_c: Solar cell absolute operating temperature[K], q:Electron charge [1.60217733e-19Cb], k: Boltzmann's constant[ 1.380658e-23 J/K][[19,21].

2.1 PV module Parameters:
The parameters of Vikram Solar ELDORA 270 PV module are considered for the design of conventional and proposed hybrid, optimal array configurations/ topologies are tabulated in table1. Maximum power of each PV module in an array are 270W and cells per module are 72. Maximum obtained voltage are 34.7 V. This PV module is available in Matlab/simulink environment and used for the modeling of conventional and proposed PV array configurations.

### Table 1: Vikram Solar ELDORA 270 PV module Parameters under STC (1000 W/m² and 25°C)

| Parameters                      | Values  |
|---------------------------------|---------|
| Maximum Power                   | 270 W   |
| Cells per module                | N_{cell} |
| 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 @VOC    | V_{oc}  | -0.3583% /°C |
| Temperature coefficient         | I_{sc}  | 0.024975% /°C |
| Light generated current         | I_{L}   | 8.1924 A |
| Diode saturation current        | I_{D}   | 2.4871e-10 |
| Diode ideality factor           | I_{sh}  | 0.98223 |
| Shunt resistance                | R_{sh}  | 3126.5623 Ω |
| Series resistance               | R_{s}   | 0.52303 Ω |

III. SYSTEM DESIGN

The simple 5x5 size PV plant consisting of M number of modules connected in one string are 5 and N number of parallel connected string are 5 connected to the electrical grid or load through power electronic conditioning equipments as shown in figure-2. In this paper, only concentrate on performance analysis of 5x5x size different conventional and proposed hybrid PV array configurations or topologies but not concentrate on grid integration of solar PV system through power electronics interface system. For performance analysis of proposed hybrid and optimal configurations are modeled in matlab-simulink environment and compare the best configuration with respect to shading losses, array maximum power and number of interconnections required between modules in an array.

![Simple 5 x 5 size PV Plant](image)

**Figure-2. Simple 5 x 5 size PV Plant**

### 3.1 Solar PV Array Configurations or Topologies

The main conventional interconnection schemes or PV array configurations are,

a. Series connected Modules in PV array
b. Parallel connected Modules in PV array
c. Series-Parallel (S-P) connected Modules in array
d. Total-Cross-Tied (T-C-T) type PV array
e. Bridge-Linked (B-L) type PV array and
f. Honey-Comb (H-C) type PV array

All modules in array are connected in series known as series type and modules connected in parallel named as parallel type of topologies. 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 [11-13]. The proposed hybrid configurations are formed by combination of two conventional topologies and proposed optimal configuration formed by optimize the interconnections required between modules in an array[17].

The Proposed Hybrid- PV array configurations are mainly,

i. SP-TCT hybrid configuration
ii. BL-TCT hybrid configuration
iii. HC-TCT hybrid configuration
iv. BL-HC hybrid configuration
v. Proposed optimal configuration
a. Series(S)–Parallel (P) Configuration: The Solar modules S1 to S25 are connected in S-P type of connection as shown in figure-3(a). In S-P array topology, all modules are connected in series to generate a required voltage and these series connected modules known as strings are then connected in parallel to generate required output current.

b. Bridge-Linked (B-L) Configuration: In this topology, all modules in the array are connected in bridge type as shown schematic model in figure-3(b).

c. Honey-Comb(H-C) Configuration: The Schematic model of HC configuration as shown in figure- 3(c).

d. Total-Cross-Tied(T-C-T) Configuration: The Schematic model of TCT configuration as shown in figure-3(d). In this type, the output voltage and currents of the array is equal to sum of the voltages across modules in all the rows and the sum of currents in the modules in a row respectively.

e. SP-TCT Hybrid Configuration: The Schematic model of SP-TCT hybrid configuration as shown in figure-3(e).This proposed hybrid configuration is formed by combination of SP and TCT topologies.

f. BL-TCT Hybrid Configuration: The Schematic model of BL-TCT hybrid configuration as shown in figure-3(f).This configuration is formed from the BL and TCT topologies.

g. BL-HC Hybrid Configuration: The Schematic model of BL-HC hybrid configuration as shown in figure-3(g).This proposed hybrid configuration is formed by combination of BL and HC topologies.

h. Proposed Optimal Configuration: The Schematic model of Proposed configuration as shown in figure-3(h). The proposed configuration is formed from optimal interconnections of TCT configuration with the help of connection switch(CS) among the modules in the array shown in figure-4(c).

i. HC-TCT Hybrid Configuration: The Schematic model of Proposed configuration as shown in figure-3(i). This proposed hybrid configuration is formed by combination of HC and TCT topologies.

j. Modified BL Configuration: The Schematic model of Proposed configuration as shown in figure-3(j). This proposed hybrid configuration is formed from modification of interconnections of BL topology.

k. Modified HC Configuration: The Schematic model of Proposed configuration as shown in figure-3(k). This proposed hybrid configuration is formed from modification of interconnections of HC topology.

3.2. Methodology adopted for optimal interconnections of Photovoltaic Array

In the proposed optimal method, total PV array is divided into a small 2x2 size sub arrays. For the performance analysis of 2x2 array, four photovoltaic modules S1, S2, S3 and S4 are considered and modeling
with un-shaded case of irradiance 1000 W/m² and shaded case of irradiance 500 W/m². In this 2x2 array there are seven shade patterns are possible depends upon the position of number of shaded modules and these possible patterns are tabulated in table-2. Where connection switch CS=0 means tie/connection is absent and CS=1 means tie is present. The simulation results of maximum obtained power from a 2x2 array with connection switch(CS) analysis under seven possible cases are tabulated in table-2. The figure-4[14] shows the S-P,TCT and proposed optimal technique method for 2x2 photovoltaic array.

![Schematic diagrams of PV Array Topologies](image)

**Figure-4:** Schematic diagrams of PV Array Topologies

The possible seven cases of a 2x2 array with PV modules S1,S2,S3 and S4 are shown in figure-5[17].

In Case-I, all modules in the array receives uniform irradiance of 1000 W/m². The max. array power obtained under uniform case with and without tie/connection is equal to 6676W, so in this case tie between modules not required. In Case II, shaded module S1 receives irradiance of 500 W/m² and remaining three modules receives 1000 W/m². The power obtained without tie is less than with tie, so in this case, a tie is required between modules.

In Case-III, IV and V: two shaded modules present 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 between 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 placed between the modules. In Case-VII, all are shaded modules. The obtained maximum power of array with and without tie are equal, in this case tie is not necessary. From the seven possible cases shown in figure-5, in cases I, III,V and VII tie is not required due to the maximum array power is same 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 array power is depends on position of number of shaded modules. In the proposed method, most of the cases a tie is not required and number of ties in between modules are reduced as compared to other array configurations.

![Possible cases for 2x2 size Photovoltaic Array](image)

**Figure-5:** Possible cases for 2x2 size Photovoltaic Array

| Case | Shadow type                        | Maximum Power $P_m$ (W) of shaded modules of irradiance 500 W/m² | Maximum Power $P_m$ (W) of shaded modules of irradiance 700 W/m² | Tie Required (Yes/No) |
|------|------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------|-----------------------|
|      |                                    | CS=0                                                              | CS=1                                                              | CS=0                                                              | CS=1                                                              |
| I    | No Shade                           | 1062                                                              | 1062                                                              | 1062                                                              | 1062                                                              | No                                                               |
| II   | One shaded module                  | 815                                                               | 851.5                                                             | 930.2                                                             | 948.4                                                             | Yes                                                              |
| III  | Two shaded modules in Series       | 801.6                                                             | 801.6                                                             | 908.1                                                             | 908.1                                                             | No                                                               |
| IV   | Two diagonally shaded modules      | 589.8                                                             | 801.6                                                             | 804.3                                                             | 908.1                                                             | Yes                                                              |
| V    | Two shaded modules in Parallel     | 589.8                                                             | 589.8                                                             | 804.3                                                             | 804.3                                                             | No                                                               |
| VI   | Three Shaded module                | 560.6                                                             | 579.2                                                             | 776.9                                                             | 790.9                                                             | Yes                                                              |
| VII  | All modules are shaded             | 542.7                                                             | 542.7                                                             | 755.3                                                             | 755.3                                                             | No                                                               |

**3.3 Various Partial Shading Patterns:**
Partial shading(PS) means modules in an array receives varying irradiances less than 1000W/m². For the performance analysis of conventional and proposed hybrid, optimal configurations of 5x5 size array total 10 proposed partial shading cases as shown in figure-6 are considered and compare the results with one un-shaded case(case-U) i.e., receives irradiance of 1000 W/m². In other cases (case 1-10), PV modules are shaded partially with different irradiance levels less than 1000 W/m² as shown in figure-6.
IV. Modeling and Simulation of conventional and proposed hybrid PV array configurations under PS cases

In this section, modeling of 5x5 size conventional and proposed hybrid solar PV array configurations are presented. For modeling of 11 conventional and proposed hybrid, optimal configurations total 10 proposed possible shading patterns are considered and analyze the output characteristics (P-V), global maximum array power, number of interconnections among modules in an array for the above 11 configurations. Finally, simulation results are presented.

4.1 Modeling of optimal interconnections for partial shading case-5

The proposed partial shading cases as shown in figure-6, from this shaded case-5 is considered for modeling of optimal interconnection configuration as explained step by step in figure-7. The optimal interconnections i.e., a, b, c, d, e, f, g, h, i, j, k, l, m, n, o and p among modules are depends upon the number of shaded models in an array. In this optimal method, the entire 5x5 size shaded modules array is divided into a small 2x2 sub arrays and optimize the number of ties required between modules by the proposed connection switch (CS) method as discussed in figure-4. The optimal number of interconnections of conventional and proposed hybrid configurations by considering 2x2 sub-array optimal method for case-5 as tabulated in table-3. The total number of ties required in case-5 for proposed optimal configuration is only 5 explained in table-4 as compared to other ten configurations and SP configuration has no ties required but output array power is less than the proposed optimal method of configuration as discussed in table-6.

![Figure 6: Proposed Different Partial Shading cases for Solar PV Topologies](image-url)

| Case | Shaded Modules |
|------|----------------|
| 1    | S S S S S S    |
| 2    | S S S S S S    |
| 3    | S S S S S S    |
| 4    | S S S S S S    |
| 5    | S S S S S S    |
| 6    | S S S S S S    |
| 7    | S S S S S S    |
| 8    | S S S S S S    |
| 9    | S S S S S S    |
| 10   | S S S S S S    |

![Table 3: Number of Ties/Interconnections between modules of solar PV configurations for case-5](table-url)
Figure 7. Proposed optimal interconnections for case-5
Table 4: Proposed optimal number of interconnections in partial shading case 5

| 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                    |
| S21            | S16, S17, S22     | 01                    | Yes                   | d = 1                    |
| -              | S2, S3, S7, S8    | 0                     | No                    | e = 0                    |
| -              | S7, S8, S12, S13  | 0                     | No                    | f = 0                    |
| -              | S12, S13, S17, S18| 0                     | No                    | g = 0                    |
| -              | S17, S18, S22, S23| 0                     | No                    | h = 0                    |
| S4             | S3, S8, S9        | 03                    | Yes                   | i = 1                    |
| -              | S8, S9, S13, S14  | 0                     | No                    | j = 0                    |
| S19            | S13, S14, S18     | 01                    | Yes                   | k = 1                    |
| S18, S23       | S19, S4           | 02                    | No                    | l = 0                    |
| S9             | S4, S5, S10       | 01                    | Yes                   | m = 1                    |
| S9, S14        | S10, S15          | 02                    | No                    | n = 0                    |
| S15, S19, S20  | S14               | 03                    | Yes                   | o = 1                    |
| S19, S20, S24, S25 | -               | 0                     | No                    | p = 0                    |

Table 5. Proposed optimal method results of interconnections between modules for cases 1-10

| 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 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0           |
| 2     | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0           |
| 3     | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0           |
| 4     | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0           |
| 5     | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0           |
| 6     | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0           |
| 7     | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0           |
| 8     | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0           |
| 9     | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0           |
| 10    | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0           |

4.2 Simulation of Conventional and Proposed Photovoltaic Array Configurations

For Simulation of conventional and proposed hybrid optimal array configurations [15-19], 5x5 size array of total 25 PV modules (5 strings and each string as 5 modules) are used and each module contains 72 series connected photovoltaic cells. 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 PV modules used in this simulation are Vikram Solar ELDORA 270 type are operates at different irradiance levels less than 1000W/m² and constant temperature of 25°C. In this paper, total 11 PV array configurations are simulated in Matlab/Simulink for total 10 different shading cases [19-21] and one uniform irradiance case - U. The figure-8,9,10 shows the simulation model of 5x5 size S-P,TCT and proposed optimal configuration for case-5.

Figure-8. Simulink model of 5x5 size SP array configuration for case-5

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V. RESULTS AND DISCUSSION

This section describes the performance and comparative analysis of conventional and proposed hybrid optimal array configurations [20-26] under one uniform irradiance case-U and 10 different partial shading scenarios. This proposed optimal method is simple to implement because it doesn't require any switches or sensors and not required any complex mathematical equations for analyzing this method. The proposed optimal interconnection method implementation is simple and cheaper as compared to other available conventional configurations. Partial shading analysis of shaded modules in an array under 14 different shading cases it results, number of interconnections required in proposed optimal method is less as compared to TCT, proposed hybrid configurations such as SP-TCT, HC-TCT, BL-TCT and BL-HC type configurations. So the cable losses are reduced and also installation cost for the photovoltaic system is reduced due to less number of ties. The shading losses are less and output power form array also improved as compared to other configurations as described in table-6. The mismatch power loss due to shading effect is given in equation 2 and 3.

Mismatch power loss or Power loss (W) = \( P_m - P_{mps} \) –(2)

Power loss (%) = \( \frac{P_m - P_{mps}}{P_m} \times 100 \) –(3)

Where \( P_m \) is maximum power obtained at full irradiation of 1000 W/m\(^2\) and \( P_{mps} \) is global maximum power obtained at different partial shading scenarios.
### Table 6: Number of Interconnections and PV array power, power loss for different array configurations

| Cases          | Configurations/ Topology | No. of Ties required | Array Power: Pm (W) | Power Loss: Ploss (W) | % Power Loss w.r.t $\frac{P_{loss}}{P_{m, A100}}$ | Best Topology w.r.t \( P_m \) | Best Topology w.r.t No.of interconnections |
|----------------|--------------------------|----------------------|---------------------|----------------------|-----------------------------------------------|---------------------------------|-------------------------------------------|
| Uniform        | SP                       | 0                    | 6676                | 0                    | 0                                             | Any one                        | 1.S-P 2.Proposed                         |
|                | BL                       | 08                   | 6676                | 0                    | 0                                             |                                |                                           |
|                | HC                       | 08                   | 6676                | 0                    | 0                                             |                                |                                           |
|                | TCT                      | 16                   | 6676                | 0                    | 0                                             |                                |                                           |
|                | SP-TCT                   | 08                   | 6676                | 0                    | 0                                             |                                |                                           |
|                | BL-TCT                   | 12                   | 6676                | 0                    | 0                                             |                                |                                           |
|                | HC-TCT                   | 12                   | 6676                | 0                    | 0                                             |                                |                                           |
|                | BL-HC                    | 12                   | 6676                | 0                    | 0                                             |                                |                                           |
|                | MBL                      | 08                   | 6676                | 0                    | 0                                             |                                |                                           |
|                | MHC                      | 08                   | 6676                | 0                    | 0                                             |                                |                                           |
|                | Proposed optimal         | 0                    | 6676                | 0                    | 0                                             |                                |                                           |
| 1              | SP                       | 0                    | 6051                | 625                  | 9.3                                           | TCT/                            | 1.Proposed                               |
|                | BL                       | 08                   | 6199                | 477                  | 7.1                                           | TCT/                            | 2.SP-TCT                                |
|                | HC                       | 08                   | 6255                | 421                  | 6.3                                           |                                |                                           |
|                | TCT                      | 16                   | 6402                | 274                  | 4.1                                           | SP-TCT/                         | 1.Proposed                               |
|                | SP-TCT                   | 08                   | 6402                | 274                  | 4.1                                           | BL-TCT/                         | 2.SP-TCT                                |
|                | BL-TCT                   | 12                   | 6402                | 274                  | 4.1                                           | HC-TCT/                         | 1.Proposed                               |
|                | HC-TCT                   | 12                   | 6402                | 274                  | 4.1                                           | BL-HC                           | 2.Proposed                               |
|                | TCT                      | 16                   | 6402                | 274                  | 4.1                                           |                                |                                           |
|                | TCT                      | 16                   | 5895                | 781                  | 11.7                                          | TCT/                            | 1.Proposed                               |
|                | MBL                      | 08                   | 5790                | 886                  | 13.2                                          |                                |                                           |
|                | MHC                      | 08                   | 5785                | 891                  | 13.3                                          |                                |                                           |
|                | Proposed optimal         | 02                   | 5570                | 1106                 | 16.5                                          |                                |                                           |
| 2              | SP                       | 0                    | 5608                | 1068                 | 16.0                                          |                                |                                           |
|                | BL                       | 08                   | 5790                | 886                  | 13.2                                          |                                |                                           |
|                | HC                       | 08                   | 5785                | 891                  | 13.3                                          |                                |                                           |
|                | TCT                      | 16                   | 5895                | 781                  | 11.7                                          |                                |                                           |
|                | SP-TCT                   | 08                   | 5895                | 781                  | 11.7                                          |                                |                                           |
|                | BL-TCT                   | 12                   | 5895                | 781                  | 11.7                                          |                                |                                           |
|                | HC-TCT                   | 12                   | 5895                | 781                  | 11.7                                          |                                |                                           |
|                | BL-HC                    | 12                   | 5895                | 781                  | 11.7                                          |                                |                                           |
|                | MBL                      | 08                   | 5790                | 886                  | 13.2                                          |                                |                                           |
|                | MHC                      | 08                   | 5785                | 891                  | 13.3                                          |                                |                                           |
|                | Proposed optimal         | 02                   | 5570                | 1106                 | 16.5                                          |                                |                                           |
| 3              | SP                       | 0                    | 6051                | 625                  | 9.3                                           |                                |                                           |
|                | BL                       | 08                   | 6129                | 547                  | 8.2                                           |                                |                                           |
|                | HC                       | 08                   | 6131                | 545                  | 8.1                                           |                                |                                           |
|                | TCT                      | 16                   | 6282                | 394                  | 5.9                                           | TCT/                            | 1.Proposed                               |
|                | SP-TCT                   | 08                   | 6195                | 481                  | 7.2                                           |                                |                                           |
|                | BL-TCT                   | 12                   | 6195                | 481                  | 7.2                                           |                                |                                           |
|                | HC-TCT                   | 12                   | 6228                | 448                  | 6.7                                           |                                |                                           |
|                | BL-HC                    | 12                   | 6201                | 475                  | 7.1                                           |                                |                                           |
|                | MBL                      | 08                   | 6082                | 594                  | 8.8                                           |                                |                                           |
|                | MHC                      | 08                   | 6078                | 598                  | 8.9                                           |                                |                                           |
|                | Proposed optimal         | 03                   | 6140                | 536                  | 8.0                                           |                                |                                           |
| 4              | SP                       | 0                    | 3844                | 2832                 | 42.4                                          |                                |                                           |
|                | BL                       | 08                   | 4059                | 2617                 | 39.2                                          |                                |                                           |
|                | HC                       | 08                   | 3891                | 2785                 | 41.7                                          |                                |                                           |
|                | TCT                      | 16                   | 4144                | 2532                 | 37.9                                          |                                |                                           |
|                | SP-TCT                   | 08                   | 4029                | 2647                 | 39.6                                          |                                |                                           |
|                | BL-TCT                   | 12                   | 4094                | 2582                 | 38.6                                          |                                |                                           |
|                | HC-TCT                   | 12                   | 4029                | 2647                 | 39.6                                          |                                |                                           |
|                | BL-HC                    | 12                   | 4130                | 2546                 | 38.1                                          |                                |                                           |
|                | MBL                      | 08                   | 3974                | 2702                 | 40.4                                          |                                |                                           |
|                | MHC                      | 08                   | 4012                | 2664                 | 40.0                                          |                                |                                           |
|                | Proposed optimal         | 04                   | 3979                | 2697                 | 40.4                                          |                                |                                           |
| 5              | SP                       | 0                    | 3844                | 2832                 | 42.4                                          |                                |                                           |
|                | BL                       | 08                   | 4141                | 2535                 | 37.9                                          |                                |                                           |
|                | HC                       | 08                   | 3919                | 2757                 | 41.3                                          |                                |                                           |
|                | TCT                      | 16                   | 4144                | 2532                 | 38.0                                          |                                |                                           |
|                | SP-TCT                   | 08                   | 4014                | 2662                 | 39.8                                          |                                |                                           |
|                | BL-TCT                   | 12                   | 4123                | 2553                 | 38.2                                          |                                |                                           |
|                | HC-TCT                   | 12                   | 4014                | 2662                 | 39.8                                          |                                |                                           |
|                | BL-HC                    | 12                   | 4130                | 2546                 | 38.1                                          |                                |                                           |
|                | MBL                      | 08                   | 4018                | 2658                 | 39.8                                          |                                |                                           |
|                | MHC                      | 08                   | 4139                | 2537                 | 38.0                                          |                                |                                           |
|                | Proposed optimal         | 05                   | 4081                | 2595                 | 38.8                                          |                                |                                           |
| 6              | SP                       | 0                    | 3844                | 2832                 | 42.4                                          |                                |                                           |
|                | BL                       | 08                   | 3973                | 2703                 | 40.4                                          |                                |                                           |
5.2 Simulation Results

The P-V Characteristics conventional and proposed hybrid optimal array configurations under 10 partial shaded cases are shown in figures 11-21. Figure-21 and 22 represents the number of interconnection required among modules in an array and global array output power for conventional and proposed hybrid optimal configurations. Under un-shaded case-U, the array power output is equal i.e., 6676W for all topologies and output power changes depends on shading patterns in an array as presented in table-6. From figure-22, the number of interconnections or ties required for proposed optimal topology is less than TCT, hybrid configurations in most shading cases as discussed in figure-6. In table-6 observations, the best topology with respect to maximum power is TCT and hybrid configurations and best topology with respect to number of interconnections among modules in an array is proposed optimal configuration up to cases 1-7 and SP topology is best for case-8 and proposed modified topologies in case-9,10.

a. Series-Parallel (S-P) Configuration

Figure-11. P-V Characteristics of 5 x 5 size Series-Parallel array configuration
b. B-L Configuration

Figure-12. P-V characteristics of 5 x 5 size BL array configuration

c. H-C Configuration

Figure-13. P-V characteristics of 5 x 5 HC array configuration

d. Total-Cross-Tied (TCT) Configuration

Figure-14. P-V characteristics of 5 x 5 array TCT configuration

e. SP-TCT Configuration

Figure-15. P-V characteristics of 5 x 5 size SP-TCT array configuration

f. BL-TCT Configuration

g. HC-TCT Configuration

Figure-16. P-V characteristics of 5 x 5 array BL-TCT configuration

h. BL-HC Configuration

Figure-17. P-V characteristics of 5 x 5 array BL-HC configuration

i. Modified BL Configuration

Figure-18. P-V characteristics of 5 x 5 array BL-HC configuration

j. Modified HC Configuration

Figure-19. P-V characteristics of 5 x 5 BL-HC configuration
power and number of interconnection among modules in an array. In this paper, Series-Parallel (SP) configurations of 2x2 size array contains four modules $S1, S2, S3, S4$ with connection switch method is studied for possible seven shading cases and optimal interconnections between modules are proposed. The proposed method is applied to any size of photovoltaic system. This optimal method is applied to small 2x2 sub arrays of 5x5 size array consisting of 25 PV modules under 10 partial shading cases. The proposed hybrid configurations are best topologies as compared to other conventional topologies and proposed optimal topology is best with respect to the number of interconnection between modules in an 5x5 array system in most cases. In the proposed optimal configuration, the installation cost of photovoltaic system, wiring time during installation and cable losses are reduced. The power output of 5x5 size array is improved and shading losses also reduced with the proposed optimal method as compared to conventional configurations. Finally, the best topology in terms of number of ties or interconnections is the proposed optimal configuration among other topologies by analyzing 10 possible shading cases.

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