

Mathematical Analysis of Solar Photovoltaic Array Configurations with Partial Shaded Modules

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Received February 24, 2020; Accepted April 22, 2020; Published April 28, 2020

Solar-based photovoltaic (SPV) cells produce power from sunlight through the photovoltaic effect. The yield voltage of a single PV cell is small, so the voltage is extended by interfacing PV cells in series arrangement known as PV module or panel. Solar PV array comprises of series and parallel connections of modules in the grid structure with a few columns and rows. The various kinds of SPV array configurations or topologies are shaped by changing the number of electrical connections between module to module in an array. This paper presents the mathematical examination of 6×6 size regular SPV array configurations, including Total-Cross-Tied, Parallel, Honey-Comb, Series-Parallel, Series, Bridge-Linked types beneath un-shading case, and different proposed shading cases (primarily short narrow, short wide, long narrow, and long wide shadings). The electrical proportionate circuit of the SPV array setups was analyzed by Kirchhoff's laws at distinctive nodes and loops in a sun powered PV array. The location of global maximum power point (GMPP) was determined hypothetically and distinguished in Matlab/simulation software at various shading conditions.

Keywords: Photovoltaic cell; Module; Array; Configurations; Shaded modules; Row currents; PV array power.

1. Introduction

The expanded electrical energy demand around the world, ecological issues, and the global warming effect due to the use of fossil fuels have brought about the developing selection of sustainable power sources for power generation. Sustainable power source is an elective wellspring of electrical energy for providing the necessary energy demand. Among all renewable energy sources, the photovoltaic (PV) system has a more preferred position than other sources, because of the most recent improvement in PV innovation, value drop of PV modules or panels, rugged and simple in design requiring very little maintenance, subsidies provided by the government, no pollution *etc.* [1]. Solar-based PV (SPV) power is gotten by the immediate transformation strategy for sunlight into power. The exhibition of the SPV system relies upon solar-based irradiance, shading effect, maturing impact, temperature, and degradation impacts, and so on. The most influencing factors are temperature and solar-based irradiance [2-3]. The sun-oriented PV system has a unique extreme power point (MPP) under uniform irradiance case, and numerous peaks happen under non-uniform irradiance cases, for example, local peaks, global peaks. This global peak point is considered on the yield P-V characteristics [4].

Solar-oriented PV cells can straightforwardly convert the sun powered capacity into the electrical power and be associated through various interconnections of cells to achieve more power. The sun-based PV panel or module is shaped by arranging PV cells in series, while the PV array is framed by the series and parallel association of PV panels. The quantity of interconnections between modules in a array are changed to make the diverse SPV exhibit association topologies, for example, Series, Bridge-Link, Parallel, Total-Cross-Tied (TCT), Series-Parallel, and Honey-Comb types [5]. Among all topologies, TCT has least mismatch, low shading losses, and high producing yield power [6]. Many researchers have introduced literature reviews on solar PV array configurations under incomplete shading conditions [7-10].

This paper presents the mathematical examination of a 6×6 SPV array arrangement under four shading cases including short narrow (SN), long wide (LW), short wide (SW) and long narrow (LN) shadings, and one un-shading case (U). The mathematical examination of a 6×6 size regular designs was gotten from Kirchhoff's laws, *i.e.*, Kirchhoff's current law (KCL) was applied at hubs, and Kirchhoff's voltage law (KVL) was applied at closed loops.

This paper initially discusses the modeling of a single diode photovoltaic cell, module, and array in Section 2. Different conventional SPV arrangements are introduced in Section 3. In Sections 4 and 5, the numerical investigation of conventional type configurations under the non-shading case and four shading cases and furthermore reproduction results for a 6×6 array designs are introduced. In Section 6, conclusions are given.

2. Modeling of Solar Photovoltaic System

2.1 Modeling of Photovoltaic Cell, Module, and Array

Sun oriented photovoltaic cells directly convert photon energy from sun based irradiance into DC electricity through the photovoltaic effect. Each cell generates a small amount of the current, and these cells are connected in series to form a single module or panel and produce higher currents. The combination of series and parallel connected PV panels forms a SPV array.

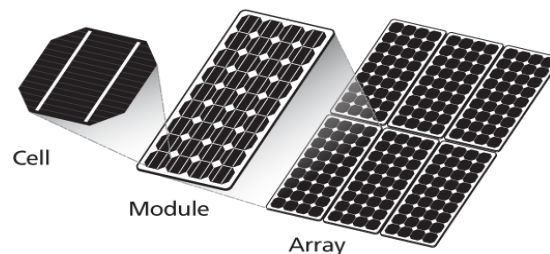


Figure 1. Formation of the solar PV cell to an array.

Figure 1 shows the formation of the SPV array with several cells and modules. The simplified models of single diode PV cell and PV array are shown in Figure 2 and

Figure 3, respectively. The solar PV array is made by series-connected (N_s) and parallel connected (N_p) PV panels.

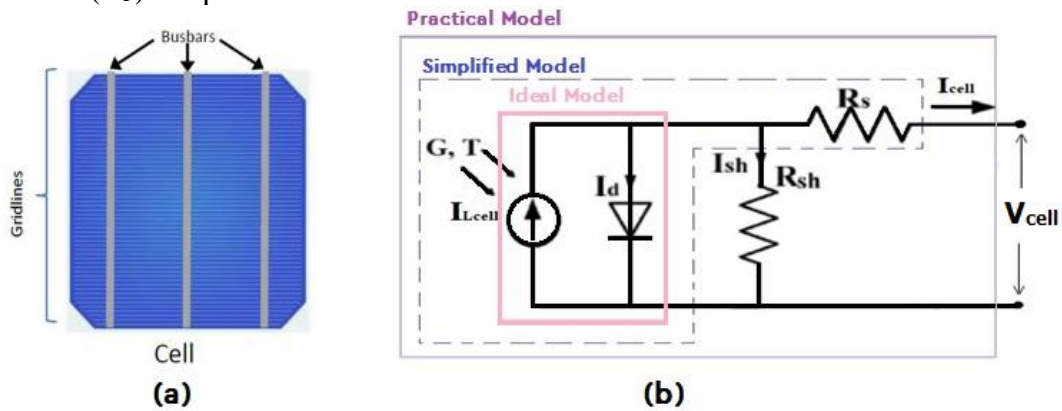


Figure 2. (a) Single diode solar PV cell (b) Equivalent circuit of a PV cell

The mathematical representation of a PV cell is given in Equation 1 [11].

$$I_{cell} = I_{Lcell} - I_0 \left[\exp \left\{ \frac{q(V_{cell} + I_{cell}R_S)}{K_a T_c} \right\} - 1 \right] - \frac{(V_{cell} + I_{cell}R_S)}{R_{SH}} \dots \dots \dots (1)$$

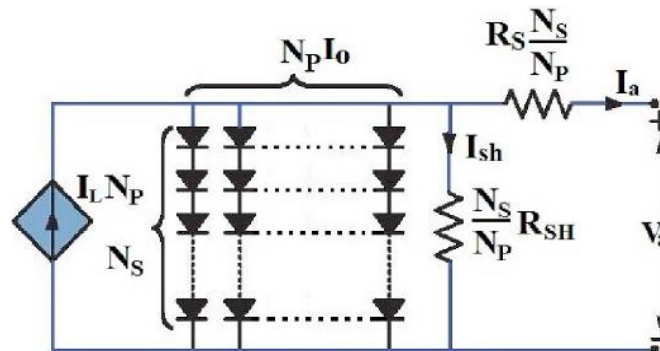


Figure 3. Circuit of solar photovoltaic array

The mathematical representation of the PV module given in Equation 2,

$$I_m = I_L - I_0 \left[\exp \left\{ \frac{q(V_m + I_m R_S)}{n_s K_a T_c} \right\} - 1 \right] - \frac{(V_m + I_m R_S)}{R_{SH}} \dots \dots \dots (2)$$

where I_L is the current generated by the module light, represented as

$$I_L = \frac{G}{G_0} [I_{LSTC} + K_{isc}(T_c - T_{STC})] \dots \dots \dots (3)$$

where, K_{isc} is the module short circuit co-efficient, I_{LSTC} the current generated by the module light at STC (Standard Test Conditions). G is the incident irradiance, and G_0 is the standard irradiance. I_m and V_m are output current and voltage of PV module, I_{cell} and

V_{cell} are output current and voltage of a single diode PV cell, I_{Lcell} is photo generated current of a solar PV cell and I_0 is reverse saturation current.

The simplified mathematical equation of PV array [10-11] is given by

$$I_a = N_p \cdot I_L - N_p \cdot I_0 \left[\exp \left\{ \frac{q(V_a + \frac{N_s}{N_p} I_a R_s)}{N_s K a T_c} \right\} - 1 \right] - \frac{(V_a + \frac{N_s}{N_p} I_a R_s)}{\frac{N_s}{N_p} \cdot R_{SH}} \quad \dots \dots (4)$$

where, N_p and N_s are the total number of parallel and series connected panels in the SPV array, R_{SH} and R_s are parallel and series resistances of the module, V_a and I_a are the voltage and current of the SPV array. I_L denotes the photo-electric current, I_0 is reverse saturation current, q : charge, a : diode ideality factor, k : Boltzmann constant and T is the temperature of the solar cell at STC.

The above set of equations is used to model the PV array to simulate I-V and P-V characteristics with the help of parameters in the datasheet of a solar PV module.

3. Solar PV Array Configurations

3.1 Conventional Solar PV Array Configurations

There are six basic PV array configurations available which are known as a conventional type of configurations or topologies. From this conventional type, hybrid PV array topologies are developed by combining any two conventional type configurations. The primary conventional configurations of PV array are [12]:

- a. Simple Series (SS) connection
- b. Series-Parallel (S-P) connection
- c. Bridge-Linked (B-L) connection
- d. Simple Parallel (SP) connection
- e. Total-Cross-Tied (T-C-T) connection
- f. Honey-Comb (H-C) connection configuration.

Figure 4 shows the conventional array configurations of a 6×6 size solar PV array.

Simple-Series (SS): In this connection, one module is connected to another module like a series connection, as shown in Figure 4(a). In a series connection, the total voltage is the sum of each module voltages, so the output array voltage is high in a SS topology.

Simple-Parallel (P): In this connection, all SPV modules are parallel connected, as shown in Figure 4(b). In a parallel connection, the total current is the sum of each module currents, so the output array current is high in a parallel topology.

Series-Parallel (SP): In this type, the number of series-connected modules called strings is connected to form a series-parallel (SP) topology, as displayed in Figure 4(c).

Bridge-Link (BL): This BL topology is adapted from a wheat-stone bridge, and this scheme is derived from the bridge rectifier connections, as shown in Figure 4(e).

Honey-Comb (HC): In this connection, solar PV panels are connected in hexagon shape by the honeycomb architecture, as shown in Figure 4(f).

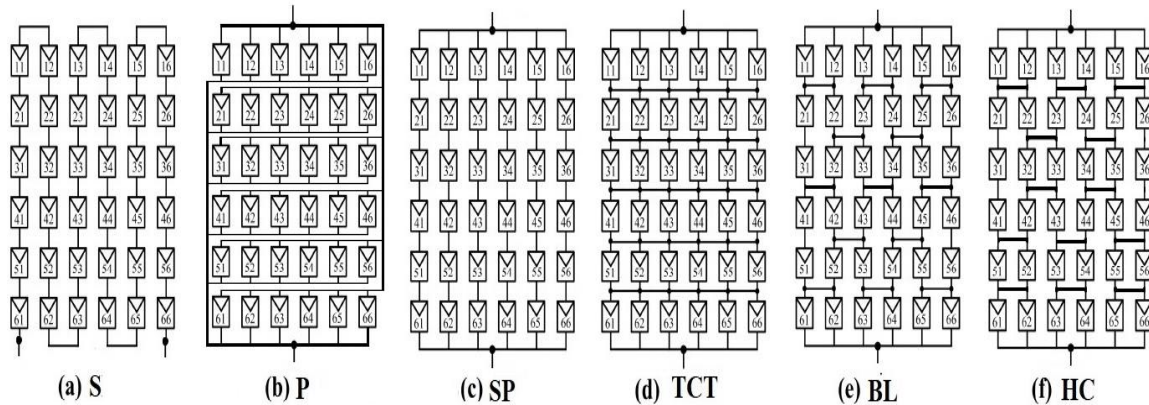


Figure 4. 6x6 Solar PV array conventional configurations

Total-Cross-Tied (TCT): This TCT connection is formed by establishing the electrical contacts or ties among the rows and columns of the S-P connection topology, as shown in Figure 4(d).

In this TCT connection, SPV modules are connected in matrix form. The labeled number **mn** in matrix form indicates; first index **m** represents the row number and second index **n** represents the column number. For example, in a 6x6 connected SPV array 1st row consists of PV modules labeling from 11 (1st row and 1st column) to 16 (1st row and 6th column), and the 1st column consists of modules from 11 (1st row and 1st column) to 61 (6th row and 1st column), as shown in Figure 4.

4. Mathematical Analysis of SPV Array Configurations

In this section, mathematical examination is performed for a 6x6 size PV array conventional configuration, appeared in Figures 5 to 10. The mathematical is performed with the assistance of Kirchhoff's laws, *i.e.*, Kirchhoff's current law is applied at nodes and Kirchhoff's voltage law is applied at closed loops.

4.1 Different Interconnection Array Configurations

(i) Simple Series Configuration

The simplest topology or configuration of the PV system is Simple Series connection type, as shown in Figure 5. Where I_{PV} and V_{PV} are the current and voltage of the PV array.

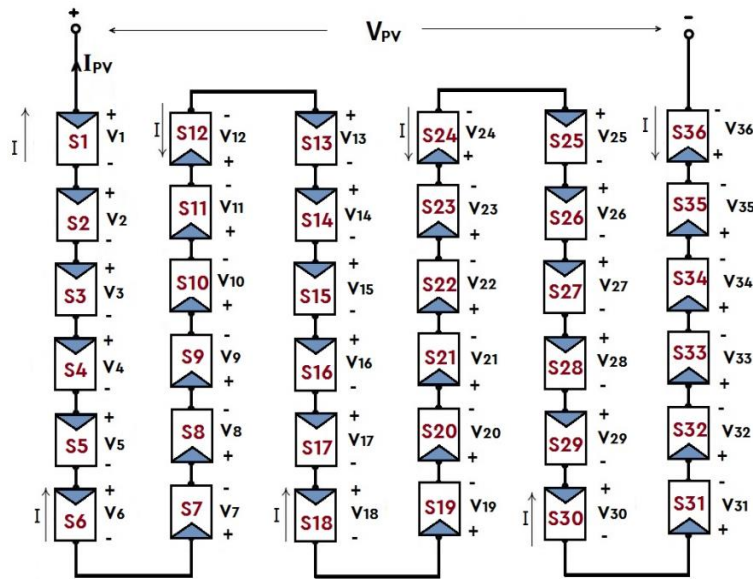


Figure 5. 6x6 Simple Series configuration

In a series connection, the same current flowing through the 36 modules in the array. Apply KVL for one closed loop in the Simple Series topology and the KVL equation is written as,

$$\sum_{n=1}^{36} V_n = V_{PV} \quad \text{--- -- (5)}$$

where n is the number of modules in an array configuration.

It is noted that a 6x6 array of SS connection has 36 module voltages and the one array current.

$$i.e., \quad V_{PV} = V_1 + V_2 + \dots + V_{36} \quad \text{--- -- (6)}$$

$$I_{PV} = I \quad \text{--- -- (7)}$$

(ii) Simple Parallel Configuration

The simple parallel configuration is shown in Figure 6. Where, I_{PV} and V_{PV} are the array current and voltage.

In a parallel configuration, all the modules have the same voltage (In any parallel, the circuit voltages are equal), *i.e.*, $V_1=V_2=\dots=V_{36}=V$ as shown in Figure 6 and different currents. Apply KCL at different nodes, then

$$\sum_{n=1}^{36} I_n = I_{PV} \quad \text{--- -- (8)}$$

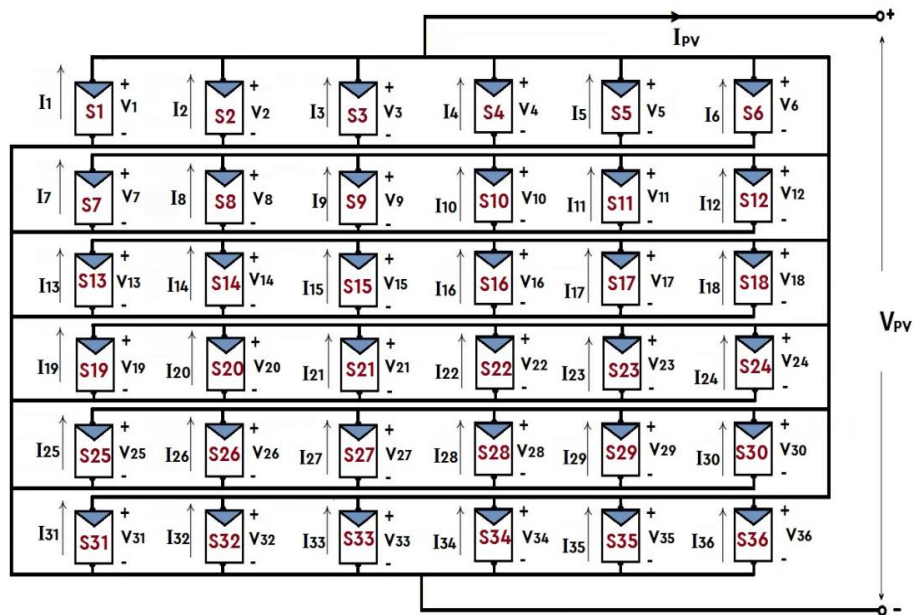


Figure 6. 6x6 Simple Parallel configuration

Where n is the number of modules in an array configuration. It is noted that a 6x6 array of parallel connection has 36 module currents and the one array voltage.

$$i.e., \quad V_{PV} = V_1 = V_2 = \dots = V_{36} = V \quad \text{--- (9)}$$

$$I_{PV} = I_1 + I_2 + \dots + I_{36} \quad \text{--- (10)}$$

(iii) Series-Parallel Configuration

The circuit of Series-Parallel (S-P) configuration of modules in an array is shown in Figure 7. This topology has four parallel strings, and each contains nine series-connected modules.

The total array current I_{PV} is equal to the sum of the six-string currents.

$$i.e., \quad I_{PV} = I_1 + I_2 + I_3 + I_4 + I_5 + I_6 \quad \text{--- (11)}$$

The six parallel string voltages are equal to the array voltage. Apply KVL at parallel strings, then the equations are given by,

$$\sum_{n=1}^6 V_n = \sum_{n=7}^{12} V_n = \sum_{n=13}^{18} V_n = \sum_{n=19}^{24} V_n = \sum_{n=25}^{30} V_n = \sum_{n=31}^{36} V_n = V_{PV} \quad \text{--- (12)}$$

The SP configuration has 36 module voltages and four-string currents. SP configuration voltages and currents in 1st, 2nd, 3rd, 4th, 5th, 6th columns are V_1 to V_6 , V_7 to V_{12} , V_{13} to V_{18} , V_{19} to V_{24} , V_{25} to V_{30} , V_{31} to V_{36} and I_1 , I_2 , I_3 , I_4 , I_5 , I_6 , respectively, which are shown in Figure 7.

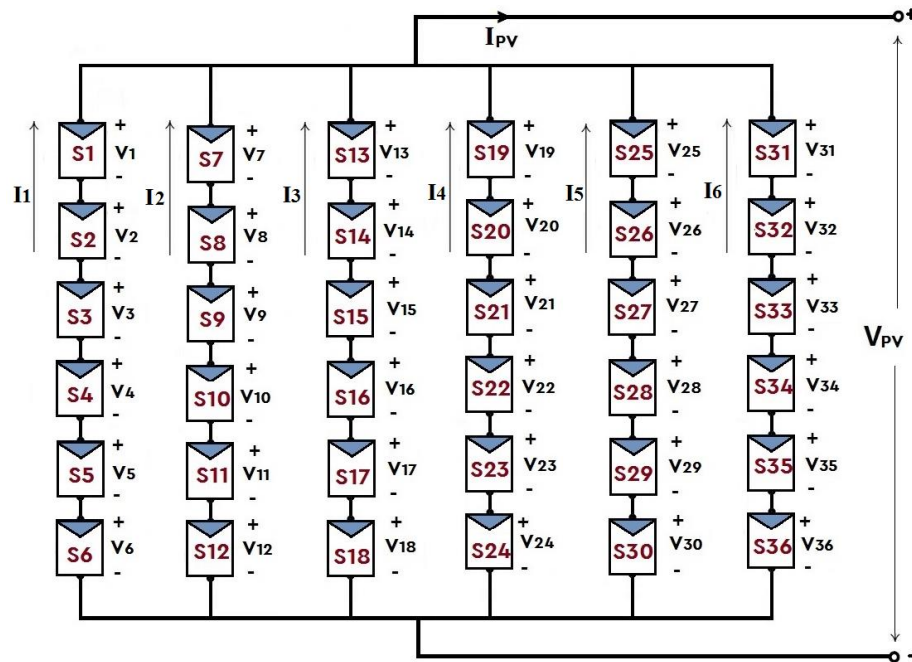


Figure 7. 6x6 Series-Parallel configuration

(iv) Total-Cross-Tied Configuration

The solar PV array with TCT configuration is shown in Figure 8. The voltage of 6 parallel modules at the m^{th} row is V_m .

where,

$$m = \begin{cases} n & \text{for } 1 \leq n \leq 6 \\ n - 6 & \text{for } 7 \leq n \leq 12 \\ n - 12 & \text{for } 13 \leq n \leq 18 \\ n - 18 & \text{for } 19 \leq n \leq 24 \\ n - 24 & \text{for } 25 \leq n \leq 30 \\ n - 30 & \text{for } 30 \leq n \leq 36 \end{cases}$$

The array voltage V_{PV} is equal to the sum of six rows of individual module voltages:

$$V_{PV} = \sum_{m=1}^6 V_m \quad \text{--- (13)}$$

$$V_{PV} = V_1 + V_2 + V_3 + V_4 + V_5 + V_6$$

Where,

$$\begin{aligned} V_1 &= V_1 = V_7 = V_{13} = V_{19} = V_{25} = V_{31} \\ V_2 &= V_2 = V_8 = V_{14} = V_{20} = V_{26} = V_{32} \\ V_3 &= V_3 = V_9 = V_{15} = V_{21} = V_{27} = V_{33} \\ V_4 &= V_4 = V_{10} = V_{16} = V_{22} = V_{28} = V_{34} \\ V_5 &= V_5 = V_{11} = V_{17} = V_{23} = V_{29} = V_{35} \\ V_6 &= V_6 = V_{12} = V_{18} = V_{24} = V_{30} = V_{36} \end{aligned}$$

Apply KCL at nodes 1 to 5, as shown in Figure 8.

$$\sum_{m=0}^5 (I_{6,m+q} - I_{6,m+(q+1)}) = 0; \quad q = 1,2,3,4,5; \quad \text{--- (14)}$$

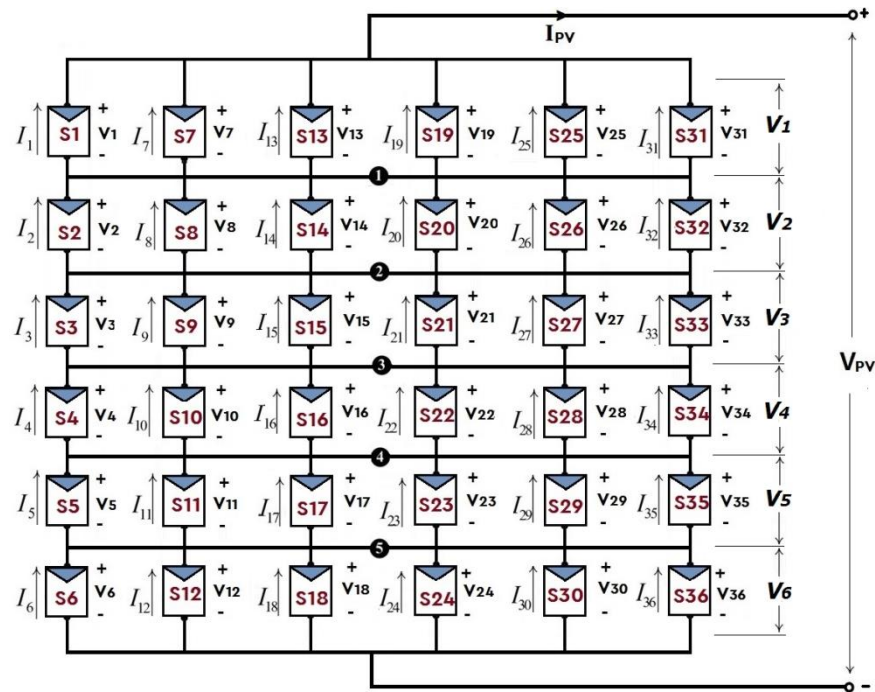


Figure 8. 6x6 Total-Cross-Tied configuration

The TCT topology has 36 module currents and 6 module voltages, as shown in Figure 8. TCT configuration has currents in 1st, 2nd, 3rd, 4th, 5th, 6th columns, which are I_1 to I_6 , I_7 to I_{12} , I_{13} to I_{18} , I_{19} to I_{24} , I_{25} to I_{30} , I_{31} to I_{36} , and voltages in 1st row to 6th rows are V_1 to V_6 .

(v) Bridge-linked Connection Configuration

The solar PV array with B-L configuration is shown in Figure 9. The module currents and voltages are I_m and V_p , respectively. The subscripts m, p are related to module number n , where,

$$m = \begin{cases} 1 & \text{for } n = 1,2 \\ 2 & \text{for } n = 3,4 \\ 3 & \text{for } n = 5,6 \\ n-3 & \text{for } 7 \leq n \leq 30; \\ 28 & \text{for } n = 31,32 \\ 29 & \text{for } n = 33,34 \\ 30 & \text{for } n = 35,36; \end{cases} \quad p = \begin{cases} n & \text{for } 1 \leq n \leq 12 \\ n-6 & \text{for } n = 13,18 \\ n-1 & \text{for } 14 \leq n \leq 17 \\ n-2 & \text{for } 19 \leq n \leq 24 \\ n-8 & \text{for } n = 25,30 \\ n-4 & \text{for } n = 31,36 \end{cases}$$

In this BL type connection topology, 30 module currents and 32 voltages across modules. Figure 9 shows the 12 nodes in the BL topology.

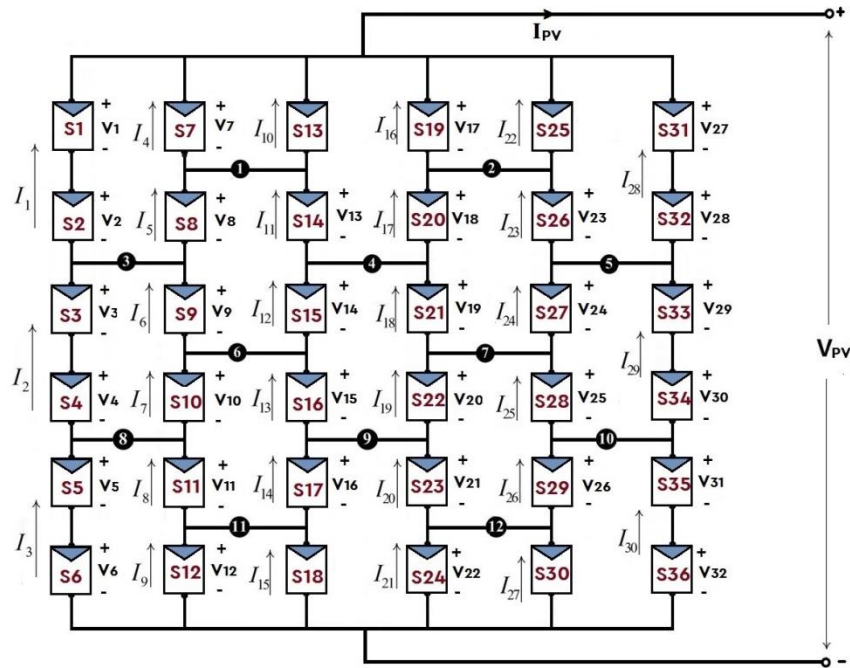


Figure 9. 6x6 Bridge-Linked configuration

The node numbers 3 and 8 at the left column, apply the KCL at node points:

$$I_m + I_q - I_{m+1} - I_{q+1} = 0; m = 1,2 \quad \text{--- (15)}$$

where the subscript q is related to m by,

$$q = \begin{cases} 5 & \text{for } m = 1 \\ 7 & \text{for } m = 2 \end{cases}$$

Similarly, apply KCL for the nodes 1, 6, 11 between 2nd & 3rd column and nodes 4, 9 between 3rd & 4th columns,

$$I_m + I_{m+6} - I_{m+1} - I_{m+7} = 0; m = 4,6,8,11,13,16,18,20 \quad \text{--- (16)}$$

For the node numbers 5,10 between 5th and 6th columns, apply the KCL at node points:

$$I_m + I_q - I_{m+1} - I_{q+1} = 0; m = 23,25 \quad \text{--- (17)}$$

in which the subscripts q and m relate to each other by,

$$q = \begin{cases} 28 & \text{for } m = 23 \\ 29 & \text{for } m = 25 \end{cases}$$

Figure 9 shows the loops and each loop contains four modules, apply KVL for the loops:

$$\begin{aligned} V_p + V_{p+1} - V_{p+6} - V_{p+7} &= 0; & p &= 1,3,5 \\ V_p + V_{p+1} - V_{p+5} - V_{p+6} &= 0; & p &= 8,10 \\ V_{p+6} + V_p - V_{p+10} - V_{p+11} &= 0; & p &= 7,17 \\ V_p + V_{p+1} - V_{p+5} - V_{p+6} &= 0; & p &= 14,18,20,24 \\ V_{p+4} + V_p - V_{p+9} - V_{p+10} &= 0; & p &= 12,22 \end{aligned} \quad \text{--- (18)}$$

Finally, apply the KVL for six modules loop in the 1st column is given by

$$\sum_{p=1}^6 V_p = V_{PV} \quad \text{--- (19)}$$

The 6×6 BL configuration has 32 voltages and 30 currents which are shown in Figure 9. BL configuration voltages and currents in 1st, 2nd, 3rd, 4th, 5th, 6th columns are V_1 to V_6 , V_7 to V_{12} , V_{13} to V_{16} , V_{17} to V_{22} , V_{23} to V_{26} , V_{27} to V_{32} and I_1 to I_3 , I_4 to I_9 , I_{10} to I_{15} , I_{16} to I_{21} , I_{22} to I_{27} , I_{28} to I_{30} , respectively.

(vi) Honey-Comb Connection Configuration

The PV array with HC connection configuration is shown in Figure 10. The module currents and voltages are I_m and V_p , respectively. The subscripts m, p are related to module number n .

where,

$$m = \begin{cases} 1 & \text{for } n = 1 \\ 2 & \text{for } n = 2,3,4 \\ 3 & \text{for } n = 5 \\ 4 & \text{for } n = 6 \\ n-2 & \text{for } 7 \leq n \leq 31 \\ 30 & \text{for } n = 32,33,34 \\ 31 & \text{for } n = 35 \\ 32 & \text{for } n = 36 \end{cases}; p = \begin{cases} n; & \text{for } 1 \leq n \leq 6 \\ 1; & \text{for } n = 7 \\ n-1; & \text{for } n = 8,9,10 \\ 5; & \text{for } n = 11 \\ 6; & \text{for } n = 12 \\ n-3; & \text{for } n = 13,14 \\ 8; & \text{for } n = 15 \\ n-4; & \text{for } n = 16,17,18 \\ 10; & \text{for } n = 19 \end{cases}; p = \begin{cases} n-5; & \text{for } n = 20,21,22 \\ 13; & \text{for } n = 23 \\ 14; & \text{for } n = 24 \\ n-7; & \text{for } n = 25,26 \\ 16; & \text{for } n = 27 \\ n-8; & \text{for } n = 28,29,30 \\ 18; & \text{for } n = 31 \\ n-9; & \text{for } n = 32,33,34 \\ 21; & \text{for } n = 35 \\ 22; & \text{for } n = 36 \end{cases}$$

In the HC connection type topology, the total number of nodes is 13. Apply KCL for each node,

$$I_m + I_q - I_{m+1} - I_{q+1} = 0; \quad m = 1,2,3,6,7,11,14,15,18,19,23,26,27 \quad \dots \dots (20)$$

and the subscript q is related to m given by

$$q = \begin{cases} 5 & m = 1 \\ 8 & m = 2 \\ 9 & m = 3 \\ 12 & m = 6 \end{cases}; q = \begin{cases} 13 & m = 7 \\ 17 & m = 11 \\ 20 & m = 14 \\ 21 & m = 15 \end{cases}; q = \begin{cases} 24 & m = 18 \\ 25 & m = 19 \\ 29 & m = 23 \\ 30 & m = 26 \\ 31 & m = 27 \end{cases}$$

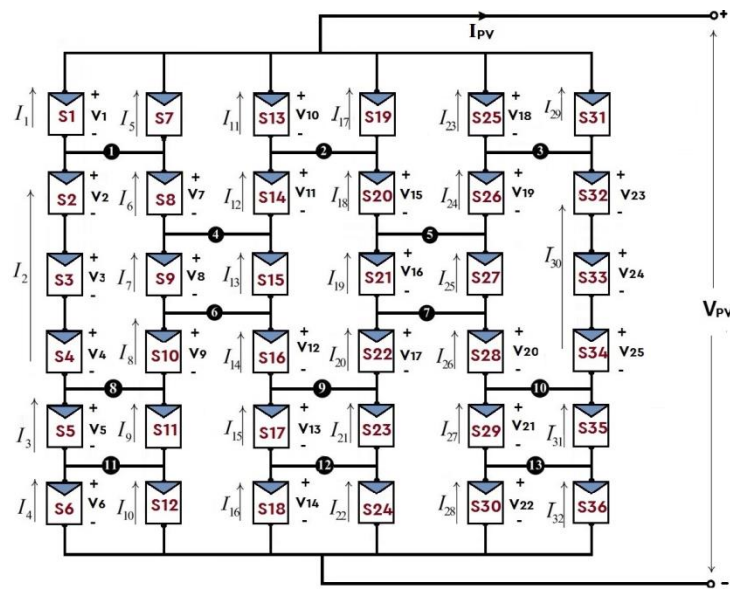


Figure 10. 6x6 Honey-Comb configuration

Then apply KVL to six or four modules in a loop,

$$\begin{aligned}
 V_p + V_{p+1} + V_{p+2} - V_q - V_{q+1} - V_{q+2} &= 0; & (p, q) &= (2, 7) \\
 V_q + V_p - V_{p+3} - V_{p+4} &= 0; & (p, q) &= (7, 1) \& (15, 10) \\
 V_p + V_{p-3} + V_{p+1} - V_{p+4} - V_{p+5} - V_{p+6} &= 0; & p &= 11, 19 \\
 V_p + V_{p-4} + V_{p-3} - V_q - V_{q+1} - V_{q+2} &= 0; & (p, q) &= (9, 12) \& (17, 20)
 \end{aligned}$$

---(21)

Finally, apply KVL for the six modules loop in the left column is given as,

$$\sum_{n=1}^6 V_n = V_{PV}$$

--- (22)

In 6x6, HC configuration has 25 module voltages and 32 currents, as shown in Figure 10. HC configuration has voltages and currents in 1st, 2nd, 3rd, 4th, 5th, 6th columns are V_1 to V_6 , V_7 to V_9 , V_{10} to V_{14} , V_{15} to V_{17} , V_{18} to V_{22} , V_{23} to V_{25} and I_1 to I_4 , I_5 to I_{10} , I_{11} to I_{16} , I_{17} to I_{22} , I_{23} to I_{28} , I_{29} to I_{32} , respectively.

Mathematical analysis of 6x6 PV connection configurations is tabulated in Table 1. Where P_{PV} , V_{PV} and I_{PV} are the output power, voltage and current of the SPV array respectively, V and I are the voltage and current output of a single PV module respectively.

4.2 Generation of Power Across the TCT array configuration

In this section, the power generation of SPV array with TCT configuration is discussed and output voltage, current and power of an array are theoretically calculated.

The current I generated by a single solar module at any irradiance G is given as,

$$I = \left(\frac{G}{G_0}\right) \cdot I_m \quad \text{--- -- (23)}$$

where G is irradiance at shading condition, and G_0 is the standard irradiance of 1000 W/m². If the solar module receives full irradiance, the output current of the module is more and vice-versa.

The PV array voltage V_{PV} is given as the summation of individual module voltages in the rows in an array, *i.e.*,

$$V_{PV} = \sum_{p=1}^n V_{mp} \quad \text{--- -- (24)}$$

where V_{mp} is the maximum module voltage at p^{th} row. In a 6x6 TCT SPV array configuration, number of rows are 6, each row voltage is V_m (the maximum module voltage), so the total voltage of an array is equal to the sum of row voltage. By neglecting the voltage drop across diodes, the SPV array voltage is given as,

$$V_{PV} = V_{m1} + V_{m2} + V_{m3} + V_{m4} + V_{m5} + V_{m6}$$

where, V_{m1} to V_{m6} are the maximum voltage of parallel connected modules in rows. Each row has 6 number of modules are connected in parallel and the row voltage is equal to V_m (total voltage is same as individual voltages in parallel connection), then

$$V_{PV} = 6 V_m \quad \text{--- -- (25)}$$

By applying the Kirchhoff's current law, the output current of an TCT SPV array configuration (current across each node in an array) is given by,

$$I_{PV} = \sum_{q=1}^n (I_{pq} - I_{(p+1)q}) = 0; \quad \text{where, } p = 1, 2, \dots, (n-1) \quad \text{--- -- (26)}$$

where, p and q are the number of rows and columns of the SPV array.

For a 6x6 solar PV array TCT configuration, the number of rows is six are connected in series and number of modules per row is 6 are connected in parallel. The total array current is the sum of six number of module currents in each row given as,

$$I_{PV} = I_{m1} + I_{m2} + I_{m3} + I_{m4} + I_{m5} + I_{m6}$$

where, I_{m1} to I_{m6} are the maximum current of parallel connected modules in rows. Each row has 6 number of modules are connected in parallel and maximum current of each

module is equal to I_m (total current is the sum of individual module currents in parallel connection), then

$$I_{PV} = 6 I_m \quad \text{--- (27)}$$

where I_m is the maximum generated current of each PV module in an array. Under un-shaded conditions, the power output of a 6×6 Solar PV TCT array is given as,

$$P_{PV} = V_{PV} \cdot I_{PV} = 6V_m \cdot 6I_m = 36V_m \cdot I_m \quad \text{--- (28)}$$

Table 1. Parameters (V, I and P) of a 6×6 SPV Array Topologies

Configurations	OUTPUT		
	Array Voltage V_{PV} (V)	Array Current I_{PV} (A)	Array Power P_{PV} (W)
Simple Series	$V_{PV} = \sum_{n=1}^{36} V_n = 36 V$	$I_{PV} = I$	$P_{PV} = 36 VI$
Simple Parallel	$V_{PV} = V$	$I_{PV} = \sum_{n=1}^{36} I_n = 36 I$	$P_{PV} = 36 VI$
Series-Parallel	$V_{PV} = \sum_{n=1}^6 V_n = 6 V$	$I_{PV} = \sum_{n=1}^6 I_n = 6 I$	$P_{PV} = 36 VI$
Total-Cross-Tied	$V_{PV} = \sum_{n=1}^6 V_n = 6 V$	$I_{PV} = \sum_{n=1}^6 I_n = 6 I$	$P_{PV} = 36 VI$
Bridge-Link	$V_{PV} = \sum_{n=1}^6 V_n = 6 V$	$I_{PV} = I_1 + I_4 + I_{10} + I_{16} + I_{22} + I_{28} = 6 I$	$P_{PV} = 36 VI$
Honey-Comb	$V_{PV} = \sum_{n=1}^6 V_n = 6 V$	$I_{PV} = I_1 + I_5 + I_{11} + I_{17} + I_{23} + I_{29} = 6 I$	$P_{PV} = 36 VI$

5. Mathematical Analysis of Partial Shaded SPV Array with TCT Configurations

5.1 Row Currents and Output Powers of the SPV Array with TCT topology

Figure 12 shows the partially shaded modules in the 6×6 PV array with TCT configurations [13-14]. For mathematical analysis of 6×6, TCT configuration calculates the currents in each row, array voltage, and array power [12]. The row currents are given as

$$I_{Rp} = \sum_{n=1}^6 S_{pn} I_m = S_{p1} I_m + S_{p2} I_m + S_{p3} I_m + S_{p4} I_m + S_{p5} I_m + S_{p6} I_m \quad \text{--- (29)}$$

$$\text{where, } S_{p1} = \left(\frac{G_{p1}}{G_o}\right), S_{p2} = \left(\frac{G_{p2}}{G_o}\right), S_{p3} = \left(\frac{G_{p3}}{G_o}\right), S_{p4} = \left(\frac{G_{p4}}{G_o}\right), S_{p5} = \left(\frac{G_{p5}}{G_o}\right), S_{p6} = \left(\frac{G_{p6}}{G_o}\right) \quad \text{--- (30)}$$

where p is row number, G_0 is the standard irradiance of 1000 W/m^2 , G_{p1} is the P^{th} row and 1^{st} column irradiance value in W/m^2 .

The 1^{st} -row current is given as,

$$I_{R1} = \sum_{n=1}^6 S_{1n} I_m = S_{11} I_m + S_{12} I_m + S_{13} I_m + S_{14} I_m + S_{15} I_m + S_{16} I_m \quad \text{--- (31)}$$

$$\text{Where, } S_{11} = \left(\frac{G_{11}}{G_0}\right), S_{12} = \left(\frac{G_{12}}{G_0}\right), S_{13} = \left(\frac{G_{13}}{G_0}\right), S_{14} = \left(\frac{G_{14}}{G_0}\right), S_{15} = \left(\frac{G_{15}}{G_0}\right), S_{16} = \left(\frac{G_{16}}{G_0}\right)$$

The 2^{nd} , 3^{rd} , 4^{th} , 5^{th} , and 6^{th} -row currents are given as,

$$I_{R2} = \sum_{n=1}^6 S_{2n} I_m = S_{21} I_m + S_{22} I_m + S_{23} I_m + S_{24} I_m + S_{25} I_m + S_{26} I_m \quad \text{--- (32)}$$

$$I_{R3} = \sum_{n=1}^6 S_{3n} I_m = S_{31} I_m + S_{32} I_m + S_{33} I_m + S_{34} I_m + S_{35} I_m + S_{36} I_m \quad \text{--- (33)}$$

$$I_{R4} = \sum_{n=1}^6 S_{4n} I_m = S_{41} I_m + S_{42} I_m + S_{43} I_m + S_{44} I_m + S_{45} I_m + S_{46} I_m \quad \text{--- (34)}$$

$$I_{R5} = \sum_{n=1}^6 S_{5n} I_m = S_{51} I_m + S_{52} I_m + S_{53} I_m + S_{54} I_m + S_{55} I_m + S_{56} I_m \quad \text{--- (35)}$$

$$I_{R6} = \sum_{n=1}^6 S_{6n} I_m = S_{61} I_m + S_{62} I_m + S_{63} I_m + S_{64} I_m + S_{65} I_m + S_{66} I_m \quad \text{--- (36)}$$

Since the currents are different in each row, so two or more peaks occur in output characteristics (P-V curves). In the TCT SPV array configuration, the global MPP, is the product of voltage and current of each row. The array current depends on the irradiance, and the array voltage is the same for all the rows by neglecting the voltage drop across the diodes. Solar PV array output voltage and power are given as,

$$V_{PV} = 6 V_m \quad \text{--- (37)}$$

$$P_{PV} = V_{PV} \cdot I_{PV} = 36 \cdot V_{PV} \cdot I_{PV} \quad \text{--- (38)}$$

The theoretical calculations of current, voltage, and power of TCT array topology are tabulated in Table 2.

5.3 Generation and Location of Global MPP for Shaded PV Array TCT Topology

The SPV array with TCT configuration under various shading cases are shown in Figure 12 [13]. For mathematical analysis of partially shaded conventional TCT configurations [15], four partial shading patterns are shown in Figure 11 and the irradiance of shaded panels is 500 W/m^2 are considered. There are mainly,

- (a) Short Narrow shading (SNS)
- (b) Short Wide shading (SWS)
- (c) Long Narrow shading (SNS)
- (d) Long Wide shading (SNS)
- (e) Un-shaded Case (U)

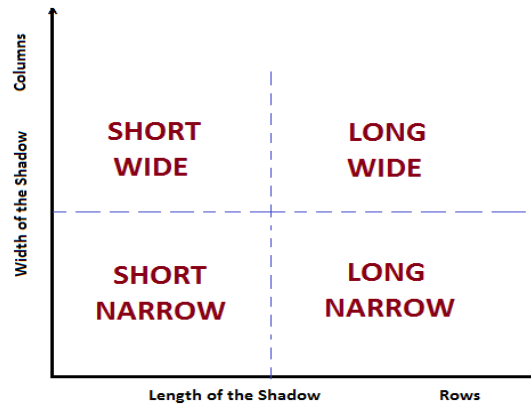


Figure 11. Types of shading cases

(a) *Short Narrow Shading (SNS)*

The short narrow type of shading scenario is observed in Figure 12(a). For formulating the location of Global Maximum Power Point (GMPP) in the output P-V characteristics theoretically, first calculate the currents in each row of the SPV array. From Figure 12(a), the 1st-row current is calculated from Equation 31,

$$I_{R1} = \left(\frac{G_{11}}{G_0}\right)I_m + \left(\frac{G_{12}}{G_0}\right)I_m + \left(\frac{G_{13}}{G_0}\right)I_m + \left(\frac{G_{14}}{G_0}\right)I_m + \left(\frac{G_{15}}{G_0}\right)I_m + \left(\frac{G_{16}}{G_0}\right)I_m$$

where, $G_{11} = G_{12} = G_{13} = G_{14} = G_{15} = G_{16} =$ irradiances at shading and G_0 is the standard irradiance of 1000W/m^2 .

From Figure 12(a): In short narrow shading, PV panels in 1st, 2nd and 3rd rows are under full uniform irradiation level of 1000 W/m^2 , while the remaining rows are under different irradiance of 500 W/m^2 . The current generated by the 1st, 2nd, and 3rd rows are calculated as follows:

$$I_{R1} = I_{R2} = I_{R3} = \left(\frac{1000}{1000}\right)I_m + \left(\frac{1000}{1000}\right)I_m + \left(\frac{1000}{1000}\right)I_m + \left(\frac{1000}{1000}\right)I_m + \left(\frac{1000}{1000}\right)I_m + \left(\frac{1000}{1000}\right)I_m = 6 I_m \text{ ---(i)}$$

Modules in row 4th, 5th and 6th are shaded and the corresponding row currents are given by,

$$I_{R4} = I_{R5} = I_{R6} = \left(\frac{1000}{1000}\right)I_m + \left(\frac{1000}{1000}\right)I_m + \left(\frac{1000}{1000}\right)I_m + \left(\frac{500}{1000}\right)I_m + \left(\frac{500}{1000}\right)I_m + \left(\frac{500}{1000}\right)I_m = 4.5 I_m \text{ --(ii)}$$

From the row currents given in *i* and *ii*, it is observed that the currents in different rows are changing from $4.5 I_m$ to $6 I_m$. Due to these varying currents, multiple peaks are generated in the output characteristics.

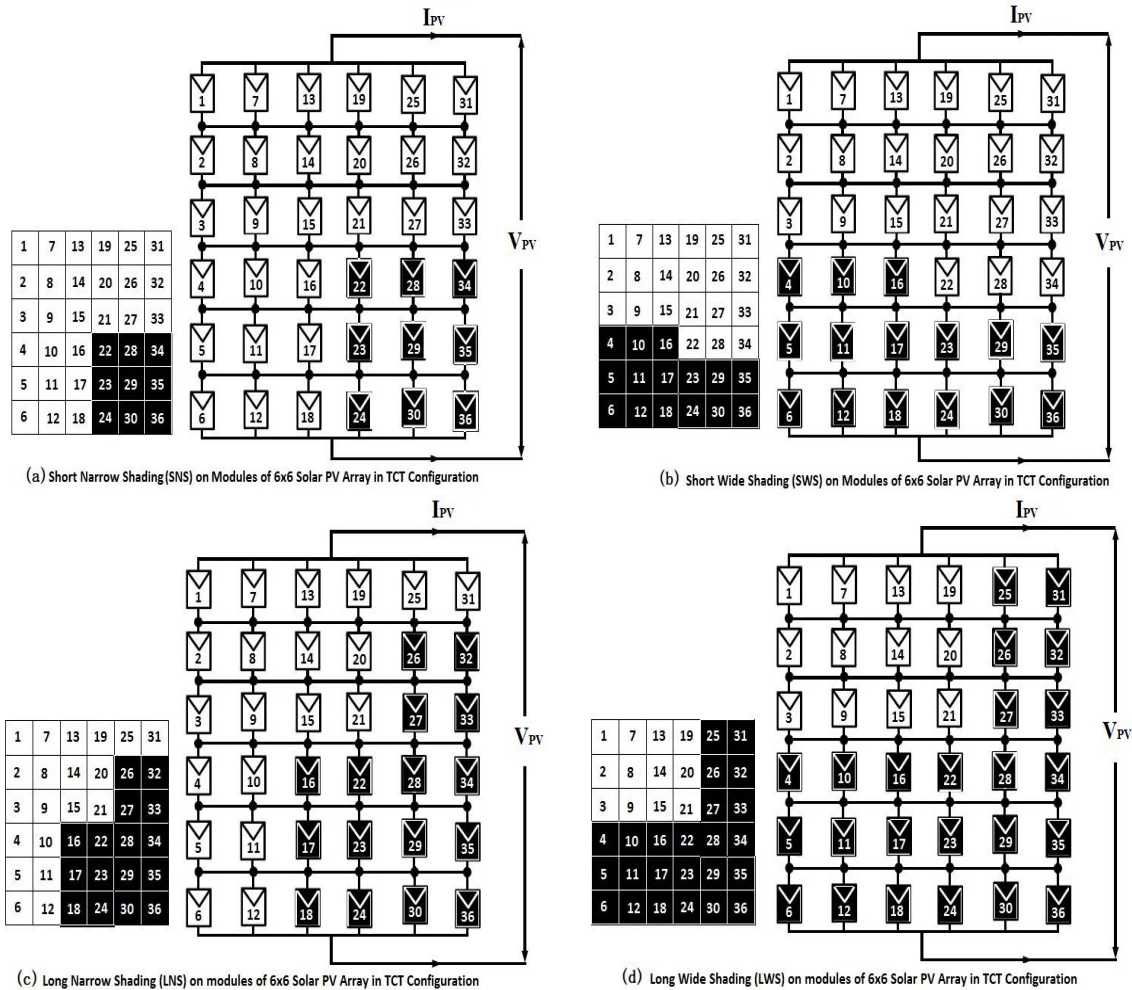


Figure 12. 6x6 Solar array with TCT configuration under various shading conditions

The maximum generated power of SPV array configuration under uniform irradiance of 1000 W/m^2 is given as

$$P_{PV} = V_{PV} \cdot I_{PV} = 6 V_m \cdot 6 I_m = 36 V_m I_m \quad \text{---- (39)}$$

where V_m is the maximum voltage. In the TCT topology, there are six series-connected modules, the voltage across the PV Array is $6V_m$ and the array current is $4.5I_m$, due to the limitation of the array current in series-connected modules in the array topology. There is no module bypassed through the bypass diode, so the array voltage is $6V_m$.

In the TCT topology under short narrow shading case without bypassing the solar modules, the total array output power is given as

$$P_{PV,TCT} = (6 V_m) * (4.5 I_m) = 27 V_m I_m \quad \text{----(40)}$$

(b) Short Wide Shading (SWS)

The short wide shading pattern can be observed in Figure 12(b). In this shading case, PV modules in 1st, 2nd, 3rd rows receive an irradiance of 1000 W/m², while the remaining modules in rows are under shaded with solar irradiance of 500 W/m². The current generated by the 1st, 2nd, and 3rd rows are calculated as follows:

$$I_{R1} = I_{R2} = I_{R3} = \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m = 6 I_m$$

Modules in row 4th, 5th and 6th are shaded. Corresponding row currents are given by,

$$I_{R4} = \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m = 4.5 I_m$$

$$I_{R5} = I_{R6} = \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m = 3 I_m$$

(c) *Long Narrow Shading (LNS)*

The long narrow shading pattern can be observed in Figure 12(c). In this shading case, PV modules in 1st row receive irradiance of 1000 W/m², while the remaining modules in rows are shaded with an irradiance of 500 W/m². Then the current in 1st row is calculated as follows:

$$I_{R1} = \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m = 6 I_m$$

PV Modules in 2nd, 3rd, 4th, 5th and 6th rows are under shading, and corresponding row currents are given by,

$$I_{R2} = I_{R3} = \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m = 5 I_m$$

$$I_{R4} = I_{R5} = I_{R6} = \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m = 4 I_m$$

(d) *Long Wide Shading (LWS)*

The LWS shading case is observed in Figure 12(d). Assume shading modules have irradiance of 500 W/m². In this type of shading case, all rows are shaded. From Figure 9(d): In long wide shading, PV modules in all rows are under shaded with solar irradiance of 500 W/m². The current generated by the 1st, 2nd, 3rd, 4th, 5th, and 6th rows are calculated as follows: Row current is calculated from Equation 31.

$$I_{R1} = I_{R2} = I_{R3} = \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{1000}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m = 5 I_m$$

The PV modules in 4, 5, 6th rows are shaded, and corresponding row currents are given by,

$$I_{R4} = I_{R5} = I_{R6} = \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m + \left(\frac{500}{1000}\right) I_m = 3 I_m$$

The currents generated in six rows in an array configuration are different due to non-uniform irradiance falling on the modules in an array configuration, which results in

the multiple peaks occur on the output P–V characteristics. The location of global MPP in output PV characteristics of conventional array topologies under different shading cases are tabulated in Tables 2 and 3, and the module currents in each row are based on the order in which modules were bypassed. By neglecting the voltage drops across the diodes and voltage variations across individual rows, then

The voltage of PV array is given as, $V_{PV}=6 V_m$.

Total Array power is given as, $P_{PV} = V_{PV} \cdot I_{PV}$. ----(41)

In Table 2, the array current I_{PV}^* denotes the minimum of six-row currents due to series connection of six modules, and the current is limited to minimum row current. Only the minimum current will flow through the array configurations[16-17].

(e) *Un-Shaded Case-U:*

In the un-shade case, 36 PV modules in a 6×6 array TCT configuration receive uniform irradiance of 1000 W/m². The parameters are calculated under uniform irradiance case by equation 24 to 28,

The array current $V_{PV} = 6 I_m$

array voltage $I_{PV} = 6 V_m$ and

array power $P_{PV} = 36 V_m I_m$. ----(42)

5.3 Theoretical Calculations and Discussions

In this paper, mathematical analysis of a 6×6 size, solar based PV array configurations is performed under four shading cases including short narrow, short wide, long narrow, and long wide types of partial shadings, as appeared in Figures 12(a) to 12(d). Table 3 demonstrates the hypothetical figuring to determine the maximum global power for the Total-Cross-Tied PV array design. Under uniform irradiance implies the non-shading case, the TCT configuration has an extreme maximum array power of $36 V_m I_m$; while in shading cases, the currents in each row are different because of progress in irradiance on the PV modules in an array and corresponding power also changed. In the case of short narrow shading (SNS), the minimum current is $4.5 I_m$ from the rows 4th, 5th, 6th, and remaining row currents are equal to $6 I_m$. Modules are connected in series due to this; the current is limited to the minimum current of rows[16-17], so the array current is $4.5 I_m$, and array voltage is $6 V_m$. The resultant array power is $27 V_m I_m$. In the remaining three shading cases, the energy yield of the PV array TCT configuration is less than the SNS case. The theoretical results are tabulated in Table 3 for the TCT 6×6 PV array configuration. In series connections, high voltages are generated by PV modules and high currents are produced in parallel connections. In S-P and TCT connections, the output power of the array is more under short narrow case as compared to other shading cases.

From the mathematical analysis of a 6×6 size solar PV array configurations, it can be concluded that:

* In the simple series connection type of configuration, under uniform irradiance case, the maximum current (I_m) is produced by the SPV modules of an array. Under shading cases, limitation due to the minimum current of $0.5 I_m$ (is determined from Equation 31) with an irradiance of 500 W/m^2 , the voltage is V_m and neglect voltage drops across diodes. The resultant array power is only $18 V_m I_m$, while in uniform case it is $36 V_m I_m$.

* In the simple parallel connection type of configurations, under uniform irradiance case the maximum current (I_m) is produced in each parallel connected modules in the PV array. Under shading cases, different currents are created and determined from Equation 31. In the short narrow case, the array current and voltage is $31.5 I_m$ and V_m , and neglect voltage drops across diodes. The resultant array power is only $31.5 V_m I_m$, though in uniform case it is $36 V_m I_m$.

* In the Series-Parallel connection type of configurations, under uniform irradiance case the array current is the aggregate of six-string currents (series connection of modules), *i.e.*, $6 I_m$, array voltage is $6 V_m$, and the resultant array power is $36 V_m I_m$. Under the short narrow case, because of shading with irradiance of 500 W/m^2 , the array current is $4.5 I_m$, the array voltage across 6 PV modules is $6 V_m$, and the resulting array power is $27 V_m I_m$.

* In the TCT connection type of configurations, under uniform irradiance case, the array current, the voltage, and the power are $6 I_m$, $6 V_m$, and $36 V_m I_m$, respectively. In short narrow shading case, row 4, 5, 6 has a minimum current of $4.5 I_m$, and the voltage is $6 V_m$ (neglecting voltage drops across the diodes). When the rows in the configuration are connected in series, because of limitation in series current, the array current is limited to $4.5 I_m$ and the resultant power is $27 V_m I_m$.

* In the B-L connection type of configurations, under uniform irradiance case, the maximum array current in parallel strings is $6 I_m$, the voltage is $6 V_m$ and the array power is $36 V_m I_m$. Under different shading cases, the output power of the array is changed.

* In the H-C connection type of configurations, under uniform irradiance case, the array current is $6 I_m$, the voltage is $6 V_m$ and the power is $36 V_m I_m$. The output power of an array configuration is changed, and it depends upon the shading pattern.

Theoretical calculations of different solar PV array configurations are presented in Table 2 and 3.

Table 2. Theoretical calculations of the location of GMPP in PV array with S, P and S-P configurations under irradiance of 500 W/m^2

Configuration	Simple Series			Simple Parallel			Series-Parallel		
	Array Current (I_{PV})	Array Voltage (V_{PV})	Array Power (P_{PV})	Array Current (I_{PV})	Array Voltage (V_{PV})	Array Power (P_{PV})	Array Current (I_{PV})	Array Voltage (V_{PV})	Array Power (P_{PV})
Uniform case	$I_{PV} = I_m$	$36 V_m$	$36 V_m \cdot I_m$	$I_{PV} = 36 I_m$	V_m	$36 V_m \cdot I_m$	$I_{PV} = 6 I_m$	$6 V_m$	$36 V_m \cdot I_m$
Short Narrow	$I_{PV} = 0.5 I_m$	$36 V_m$	$18 V_m \cdot I_m$	$I_{PV} = 31.5 I_m$	V_m	$31.5 V_m \cdot I_m$	$I_{PV} = 4.5 I_m$	$6 V_m$	$27 V_m \cdot I_m$
Short Wide	$I_{PV} = 0.5 I_m$	$36 V_m$	$18 V_m \cdot I_m$	$I_{PV} = 28.5 I_m$	V_m	$28.5 V_m \cdot I_m$	$I_{PV} = 3 I_m$	$6 V_m$	$18 V_m \cdot I_m$
Long Narrow	$I_{PV} = 0.5 I_m$	$36 V_m$	$18 V_m \cdot I_m$	$I_{PV} = 28 I_m$	V_m	$28 V_m \cdot I_m$	$I_{PV} = 4 I_m$	$6 V_m$	$24 V_m \cdot I_m$
Long Wide	$I_{PV} = 0.5 I_m$	$36 V_m$	$18 V_m \cdot I_m$	$I_{PV} = 24 I_m$	V_m	$24 V_m \cdot I_m$	$I_{PV} = 3 I_m$	$6 V_m$	$18 V_m \cdot I_m$

Table 3. Theoretical calculations of the location of GMPP in SPV Array with TCT configuration under irradiance of 500 W/m²

Shading Cases	Order of row currents in which the modules are bypassed (I_R)	Array Voltage (V_R)	Array Power ($P_{PV} = V_R \cdot I_R$)	Location of GMPP (P_{PV})
Un-Shaded Case (U)	$I_{R6} = 6 I_m$ $I_{R5} = 6 I_m$ $I_{R4} = 6 I_m$ $I_{R3} = 6 I_m$ $I_{R2} = 6 I_m$ $I_{R1} = 6 I_m$	$6 V_m$ $6 V_m$ $6 V_m$ $6 V_m$ $6 V_m$ $6 V_m$	$36 V_m \cdot I_m$ $36 V_m \cdot I_m$ $36 V_m \cdot I_m$ $36 V_m \cdot I_m$ $36 V_m \cdot I_m$ $36 V_m \cdot I_m$	$36 V_m \cdot I_m$
Short Narrow Shading (SNS)	$I_{R6} = 4.5 I_m$ $I_{R5} = 4.5 I_m$ $I_{R4} = 4.5 I_m$ $I_{R3} = 6 I_m$ $I_{R2} = 6 I_m$ $I_{R1} = 6 I_m$	$6 V_m$ $5 V_m$ $4 V_m$ $3 V_m$ $2 V_m$ V_m	$27 V_m \cdot I_m$ $22.5 V_m \cdot I_m$ $18 V_m \cdot I_m$ $18 V_m \cdot I_m$ $12 V_m \cdot I_m$ $6 V_m \cdot I_m$	$27 V_m \cdot I_m$
Short Wide Shading (SWS)	$I_{R6} = 3 I_m$ $I_{R5} = 3 I_m$ $I_{R4} = 4.5 I_m$ $I_{R3} = 6 I_m$ $I_{R2} = 6 I_m$ $I_{R1} = 6 I_m$	$6 V_m$ $5 V_m$ $4 V_m$ $3 V_m$ $2 V_m$ V_m	$18 V_m \cdot I_m$ $15 V_m \cdot I_m$ $18 V_m \cdot I_m$ $18 V_m \cdot I_m$ $12 V_m \cdot I_m$ $6 V_m \cdot I_m$	$18 V_m \cdot I_m$
Long Narrow Shading (LNS)	$I_{R6} = 4 I_m$ $I_{R5} = 4 I_m$ $I_{R4} = 4 I_m$ $I_{R3} = 5 I_m$ $I_{R2} = 5 I_m$ $I_{R1} = 6 I_m$	$6 V_m$ $5 V_m$ $4 V_m$ $3 V_m$ $2 V_m$ V_m	$24 V_m \cdot I_m$ $20 V_m \cdot I_m$ $16 V_m \cdot I_m$ $15 V_m \cdot I_m$ $10 V_m \cdot I_m$ $6 V_m \cdot I_m$	$24 V_m \cdot I_m$
Long Wide Shading (LWS)	$I_{R6} = 3 I_m$ $I_{R5} = 3 I_m$ $I_{R4} = 3 I_m$ $I_{R3} = 5 I_m$ $I_{R2} = 5 I_m$ $I_{R1} = 5 I_m$	$6 V_m$ $5 V_m$ $4 V_m$ $3 V_m$ $2 V_m$ V_m	$18 V_m \cdot I_m$ $15 V_m \cdot I_m$ $12 V_m \cdot I_m$ $15 V_m \cdot I_m$ $10 V_m \cdot I_m$ $6 V_m \cdot I_m$	$18 V_m \cdot I_m$

5.4 Simulation Results

The 6×6 solar PV array conventional topologies, mainly S-P, TCT, BL, HC types of models, are developed and simulated in Matlab/Simulink software. The Vikram solar ELDORA 270W [P_{max} is 270W] panel specifications are used in simulation of a 6×6 size SPV array with S-P, TCT, BL and HC configurations under SNS,SWS,LNS,LWS shading cases. The simulation results are tabulated in Table 4, and the maximum PV array powers observed in the TCT topology are 7714 W, 5478 W, 6865 W, and 5284 W

under proposed four shading cases, respectively. The output characteristics (V-P) of different array configurations are appeared in Figures 13 to 16.

Table 4. Simulation results of a 6×6 solar PV array configurations under different shading cases

Configuration Vs Shading Cases	Series-Parallel (S-P)	Total-Cross-Tied (TCT)	Bridge-Linked (BL)	Honey-Comb (HC)
	Array Power- P_{PV} (W)			
Uniform case	9620	9620	9620	9620
Short Narrow	7384	7714	7565	7414
Short Wide	5412	5478	5407	5434
Long Narrow	6604	6865	6765	6732
Long Wide	5154	5284	5206	5223

i. S-P Configuration P-V Characteristics

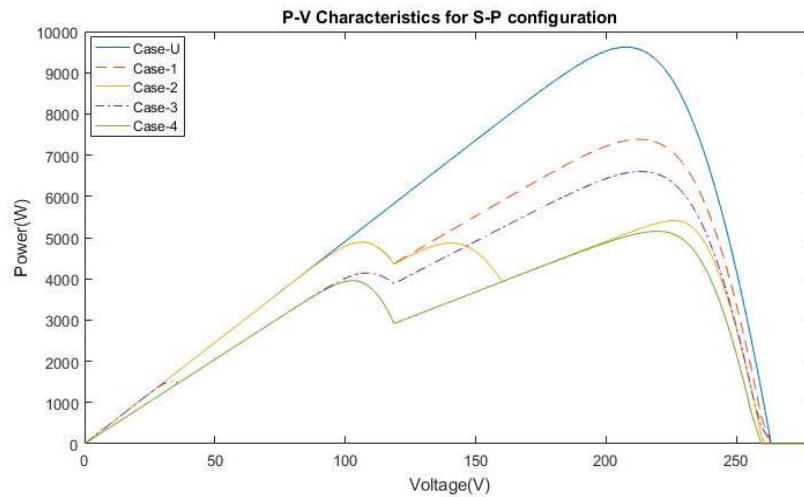


Figure 13. PV Curves for S-P type connection

ii. TCT Configuration P-V Characteristics

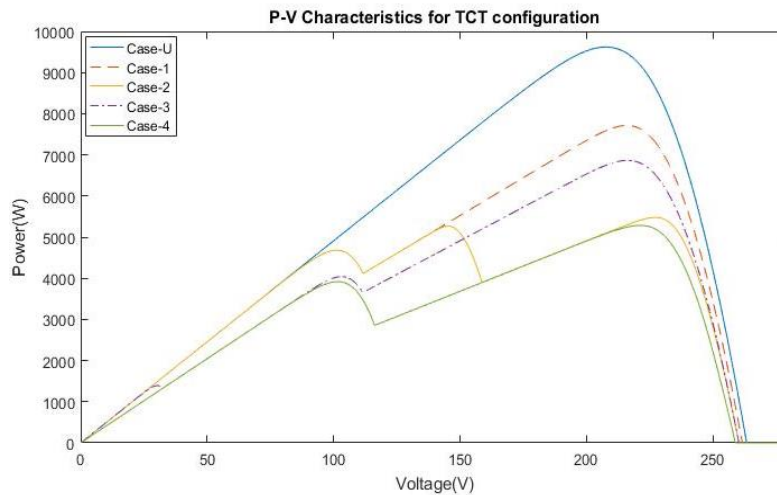


Figure 14. PV Curves for TCT type connection

iii. B-L Configuration P-V Characteristics

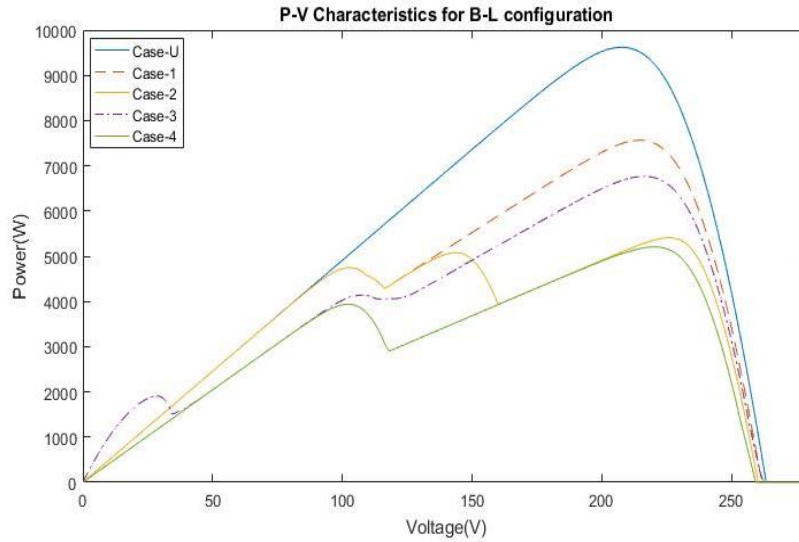


Figure 15. PV Curves for B-L type connection

iv. H-C Configuration P-V Characteristics

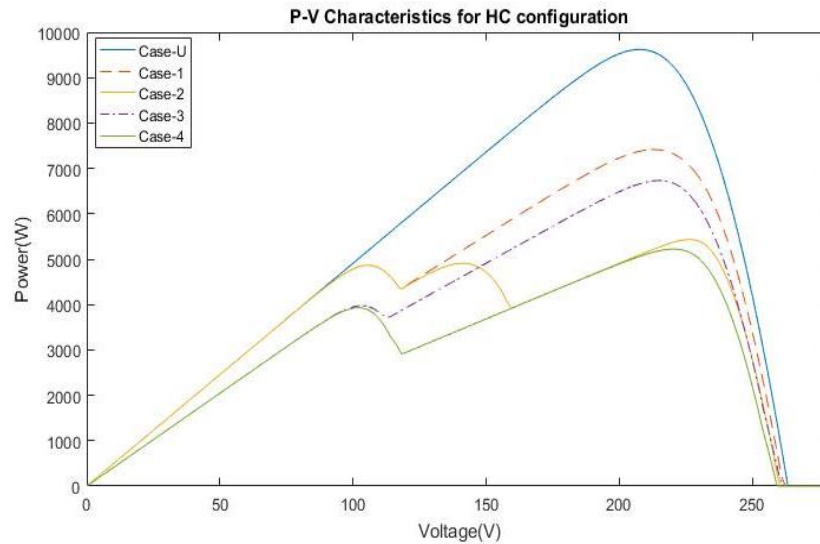


Figure 16. PV Curves for HC type connection

6. CONCLUSIONS

In this paper, mathematical investigation of conventional solar PV array configurations in particularly SS, P, SP, TCT, BL and HC types under uniform irradiance case, *i.e.*, non-shading case and proposed partial shading cases including short narrow, short wide, long narrow and long wide shading cases are presented. The 6×6 size solar PV array configurations are considered for examining under non-shading and partial

shading cases. Under various shading cases, each row current is determined based on the order of row currents, in which the modules are bypassed for the identification of a global peak power position in the output characteristics of different PV array configurations. This mathematical analysis is based on the KVL and KCL equations of a different module connections in a PV array. From the theoretical calculations and simulation analysis, the array output power is greater in TCT configuration under short narrow shading conditions. It can be concluded that the energy yield of an array relies upon the shading pattern in the SPV array configurations.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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