Intelligent Automation & Soft Computing
DOI:10.32604/iasc.2022.023331
Article

Total Cross Tied-Inverted Triangle View Configuration for PV System Power Enhancement

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Received: 03 September 2021; Accepted: 02 November 2021

Abstract: Electricity can be generated from a photovoltaic cell depending on the amount of solar radiation received from the solar system. But due to some factors such as partial shade conditions, as the thickness of the shade increases, the peak power output from the solar photovoltaic system decreases. Photovoltaic cells can be connected in parallel and in series to generate the required voltage and power. Peak power can be obtained even under shade conditions using the appropriate configuration of solar cells. A novel configuration as Total Cross Tied-Inverted Triangle View (TCT-ITV) is developed in the research by augmenting the Total Cross Tied configuration with Inverted Triangle configuration. The above system is simulated in MATLAB/SIMULINK and the performance of the system is extensively studied. Experiments have been performed under a different shading structure with the proposed TCT-ITV and compared with the existing topologies available in the literatures such as S, SP and TCT configuration, SuDoKu, magic square view topologies. It is evident from the results that the generated power using the proposed configuration increases by 7.89%, thus proving to be more efficient than the existing schemes. It can be claimed that the proposed topology performs better under large wide shaded conditions and hence used in various applications.

Keywords: Inverted triangle view; solar irradiance; partial shading; photovoltaic system

1 Introduction

Conventional source of energy on the basis of petroleum, charcoal, and gasoline have shown to be vastly efficient factors of economical growth [1]. Protection of electrical energy is necessary, so far the huge price and inadequate resources of fossil sources, along with the demand to decrease discharge of green-house gas, have made recoverable sources appealing in universal energy built economy. The capacity for these energy sources is massive since they know how to, in theory, proportionally go beyond the universal requirement of energy [2]. Along with the renewable sources of energy, the function of solar resources of energy has been growing drastically in current days because of increasing requirement of energy with least ecological effect.

The major concern in utilizing solar resources is its non-uniform properties, which varies with temperature and solar irradiation [3,4]. The properties become more complicated, if the whole solar panel does not obtain regular irradiation, as in moderately cloudy [5–7] circumstances. Typically, mechanical and electrical monitoring is employed to produce the peak power [8] from solar modules [9]. The mismatching factor is produced by partial shaded condition in electrical tracking [10–12]. Partial shading is the main reason for mismatch leakages that can decrease significantly the power production of solar PV devices. Furthermore, when a PV cell gets shadowed it turns in to corresponding to resistance that absorbs the power produced by its adjacent cell. The consumed power is transformed to thermal energy that rises the temperature and harms the cell [13].

The partial shading creates losses in power output. Various arrangements like series array, parallel array, series parallel (SP) array, TCT array, bridge-linked (BL) array, honey–comb (HC) array are comparable for their losses, cause of shunt resistance, peak power, bypass diodes and also for different sizes of panels beneath partial shading. It is noticed that the TCT configuration prevails all configurations by generating highest 4% rise in the solar panel power production [14]. A SuDoKu method was accessible to assemble the physical task of solar modules in a Total Cross Tied solar module arrangement that enhanced energy production about 3.6%, greater than the TCT arrangement. The disadvantage of this technique is an ineffectual allotment of shading and, complexity is worried in the pattern of SuDoKu technique therefore the PV panels are familiar among the vertically located arrays. It consists of a numerous limitation; also the number of modules permitted in the similar and vertical position has to be equal [15]. The limitations and difficulty of SDK pattern were reduced by the Magic Square View (MSV) pattern of solar panels Beneath PSCs; this pattern enhances the allocation of shade effect along the solar device. Moreover, there is an improvement in power of 6.38% by means of MSV technique compare to SDK pattern [16]

The major contributions of the proposed research work are listed below,

- To enhance the power efficiency and peak power can also be obtained even under shading conditions using appropriate configuration of solar cells. The Total Cross Tied configuration with Inverted Triangle View (TCT-ITV) technique is proposed. Total Cross Tied (TCT) configuration is a commonly used now-a-days because it provides maximum power even under shaded condition [17–19].
- In the proposed system, TCT-ITV configuration is proposed to regulate the location of PV cells and to increase the solar energy production beneath diverse PSCs by simulating 9 × 9 PV cell.
- Beneath Partial shading conditions, the projected configuration ITV increment the allocation of shaded collision over the solar PV array system. The solar cells [20–26] are organized based on the TCT connection and novel ITV partial shading technique is implemented.
- The performance of the system had been evaluated and the results were presented. The highlights of the proposed research are displayed systematically as follows:

Segment 2 describes the equivalent circuit of PV cell, its parameters and various connections established in solar PV module and its electric characteristics. Segment 3 describes the parameters used in solar PV module. Segment 4 displays the proposed method, its modeling and technique employed for partial shading. Segment 5 displays the simulation results, discussions and comparisons. Segment 6 provides the conclusion of the paper.

2 Modeling of Solar PV System

PV modules use the solar light energy to generate electricity using PV effect. The PV cell generates direct electrical power from sun that can be used as energy devices or for charging purposes.

2.1 Electrical Model of Photovoltaic Cell

Like a corresponding device-based structure is mostly employed for MPPT techniques. The corresponding structure of the common device comprise of a photon current, a diode, a resistance which is connected in parallel exhibiting a leakage current, resistance connected in series defining an interior resistor to the flow of electrons, is expressed in Fig. 1.

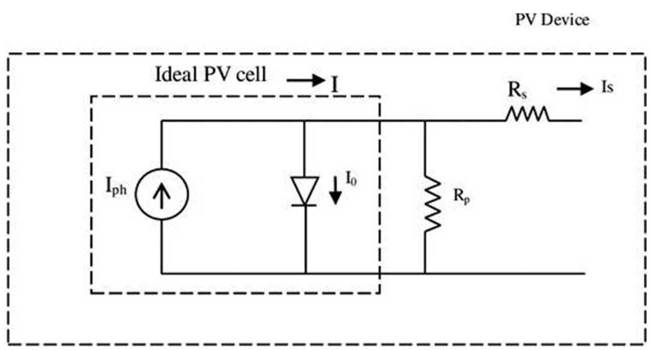

Figure 1: Electrical equivalent model of PV cell

The V-I characteristics equation of a PV cell is given by

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_s}\left[\exp\left(q\frac{(V+R_s)}{K_I T_C A}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \tag{1}$$

where,

I_{ph} is a current produced by light,

I_s is the current of cell saturation,

T_C = operating temperature of a cell,

A = ideal factor, R_{sh} = shunt resistor, R_s = series resistor

The photo electric current mostly based on the PV irradiance and operating temperature of a cell,

$$I_{ph} = [I_{sc} + K_I(T_C - T_{Ref})]\lambda \tag{2}$$

where,

I_{sc} = short circuit current of a cell at 25°C, 1 kW/m^2

K_I = temperature coefficient of short circuit current of a cell

T_{Ref} = reference temperature of a cell

2.2 Series and Series-Parallel Connected PV Topology

To produce higher voltages and currents, the cells are linked in series and parallel arrangement. Manufacturing, material, compositional requirement constraints limit the quantity of cells that can be combined in these designs. On the other hand, a pure parallel PV configuration has group of single solar cells tied up horizontally and several such strings are connected in parallel forming a parallel PV module as expressed in Fig. 2. The operation of the PV panel relies upon temperature, analysis of PV panel in addition to shading over the panel.

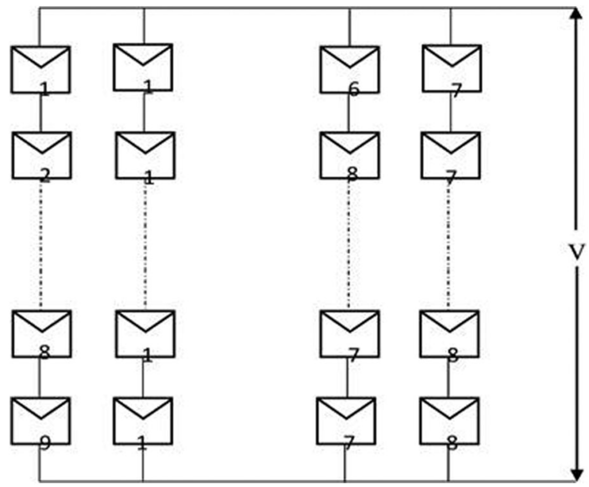

Figure 2: Series parallel connected PV

The power output from single photovoltaic cells is moderately little (approximately 0.5 W). Photovoltaic cells are linked in parallel and series it can produce necessary voltage and power. The modules are sorted by the smallest assembly design and to produce DC power. It can be mentioned before, and then the smallest amount is obtainable from producer. Modules are combined together into panels. These panels to be related mutually expand the whole array.

$$I = N_p I_L - N_p I_o \left(e^{q\left(V/N_s + IR_s/N_p\right)/(nk\ TaK)} - 1 \right) \tag{3}$$

The characteristic of the output voltage in PV system could be obtained as,

$$V_{PV} = \frac{N_s \alpha kT}{q} \ln\left[\frac{I_{sc} - I_{PV} + N_p}{N_p I_o}\right] - \frac{N_s}{N_p} R_s I_{PV} \tag{4}$$

where

N_s-Number of series cell

I_{PV}-PV cell output current

2.3 TCT Topology in PV Module

Beneath partial shading conditions, TCT arrangement need to mathematically examine to find out how these conditions influence output characteristics curves. The parameters at standard test conditions, while the current and voltage of PV module are at Maximum Power Point for specific irradiance and temperature conditions.

$$i_{pv} = i_{sc} - A.\exp\left(B.\ v_{pv}\right) \tag{5}$$

$$i_{sc} = i_{STC}\ .\ \frac{G_{pv}}{G_{STC}}\ (1 + \alpha_t.\left(T_{pv} - T_{TCT}\right) \tag{6}$$

$$B - \frac{B_{STC}}{(1 + \alpha_v.\left(T_{pv} - T_{TCT}\right)} \tag{7}$$

$$B = \frac{\ln\left(1 - \left(\frac{I_{mpp}}{i_{STC}}\right)\right)}{v_{mpp} - v_{ocSTC}} \tag{8}$$

$$A = i_{STC}.\exp(-B_{STC}.V_{ocSTC}) \tag{9}$$

Fig. 3 displays the TCT connection, modeling and the technique used in TCT is ITV configuration. The position of the module in the row does not determine the current of a row of PV modules in TCT connections. From Eq. (9) the current of a PV which has M parallel modules and voltage is obtained as below:

$$i_r = i_{eq} - \varphi\,(V_r) \tag{10}$$

$$\sum_{i=1}^{i_{eq}=} i = Mi_{sc,i}\ ,\ \varphi(V_r) = \sum_{i=1} i = M\ A_i.\exp(B_i, V_r) \tag{11}$$

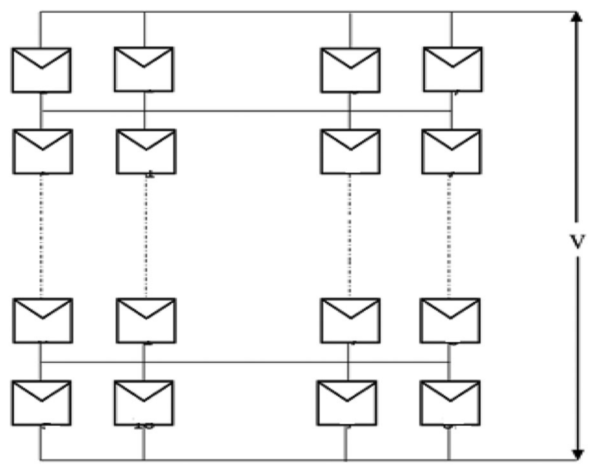

Figure 3: TCT configuration

In Eqs. (10) and (11) the module parameters are represented by ir and ieq. The row current is created by each row voltage.

$$\frac{\partial i_r}{\partial v_r} = -\sum_{i=1} i = MA_i\ .\ B_t.\exp(B_t,\ v_r) < 0 \tag{12}$$

2.4 SDK Topology in PV Module

SuDoKu is a logical related numerical array puzzle. This model consists of 9 3 × 3 matrix and every column, every row, and one of the 9 3 × 3 sub networks which compile the network comprises whole numbers from one to nine. The pattern of SuDoKu puzzle is shown in Fig. 4. The starting number in each loop declares the digit of rows and the next number denotes the column of 9 × 9 panel.

The solar array, third row and nine column is physically moved to the starting row nine column but the solar array link remains in the 9th row. Therefore, the physical locations of the Photo Voltaic arrays are accustomed devoid of varying the electrical links in the solar panel. Because of the electrical connection do not swap the electric formulas V and I remain identical as the Total Cross Tied arrangement.

11	42	53	94	25	76	87	68	39
21	92	73	84	35	66	57	18	49
31	82	63	44	55	16	97	78	29
41	32	13	54	85	96	77	28	69
51	22	93	64	75	46	17	38	89
61	72	83	24	15	36	47	98	59
71	12	23	34	45	56	67	88	99
81	62	43	74	95	26	37	58	19
91	52	33	14	65	86	27	48	79

Figure 4: The SDK pattern

2.5 MSV Topology of PV Module

An order(n = 9) of Magic Square View is a method of n^2 number, typically several digits, in square, in such a manner the n number in whole rows and columns, and the two diagonals added to the identical constant. Therefore, the Magic Square View technique shown in Fig. 5. Then the second digit is hold at location $(i - 1; j + 1)$, where every row and column considered in round module that is they enfold approximately. Also, in order to produce the Magic Square views of size 'n' it has two situations.

35	25	15	5	76	66	56	46	45
24	14	4	75	65	55	54	44	34
13	3	74	64	63	53	43	33	23
2	73	72	62	52	42	32	22	12
81	71	61	51	41	31	21	11	1
70	60	50	40	30	20	10	9	80
59	49	39	29	19	18	8	79	69
48	38	28	27	17	7	78	68	58
37	36	26	16	6	77	67	57	47

Figure 5: The MSV pattern

The location of succeeding digit is determined by decreasing row digit of the preceding number by 1 and increasing the column digit of the preceding number by 1. In the same way, if the computed location of column turns in to n, it will enfold nearly to 0. If the MS previously consists of a digit at the computed location, computed column location will be decreased to 2, and the computed row location will be increased to 1.

3 Methodology of Inverted Triangle View Configuration

The suggested ITV technique assigns the numbers of module reasonably for several numbers of PV modules. The electric circuit is similar but positions of the module vary with respect to the specified proportions of the solar panel.

It is a 90-degree triangle of natural numbers acquired by refilling the rows by using successive numbers, beginning from 1. Series number of row and quantity of component in the row are identical, i.e., first row has one component, and next one has two, and so on. The sum of n^{th} row is equal to $n (n^2 + 1)/2$ as displayed in Fig. 6. In this method, the component of first row is 1 and the second row has 2 and 3 as its part. The next row consists of 4, 5 and 6, and the numbers keep on in this model considerably.

47	57	67	77	6	16	26	36	37
58	68	78	7	17	27	28	38	48
69	79	8	18	19	29	39	49	59
80	9	10	20	30	40	50	60	70
1	11	21	31	41	51	61	71	18
12	22	32	42	52	62	72	73	2
23	33	43	53	63	64	74	3	13
34	44	54	55	65	75	4	14	24
45	46	56	66	76	5	15	25	35

Figure 6: Proposed TCT-ITV configurations

The proposed PV module is formed by connecting 9 * 9 solar cells in which they are arranged in series as well as in parallel and the entire module is total cross tied connection. It looks rather easy, and the ploy used in the inverted triangle algorithm and Fig. 7 displays the flowchart accessible below. The total cross tied connection configuration, Inverted triangle technique is employed to achieve better output results when compared to other partial shading conditions employed till date.

The inverted triangle technique is applied from third row to the eighth row in the entire module. The algorithm used in flowchart in displayed in Fig. 7. After providing the input to the system the process or the steps employed is formatted to a standard format and it is utilized, At last the inverted triangle is achieved in the system and it is tested and so better output is achieved. The concept employed behind flowchart in Fig. 7. The inverted triangle itself is a developing technique. In this paper, an ITV collection amplified with series parallel and series arrangements are suggested to vary the position of solar cells to improve the solar energy production. Beneath partial shading condition (PSC) the projected method augment the dispersion of shading consequence all the way through the solar module. Thus, the proposed method enables to minimize the shading of the panels and spread the shading over the whole array. Thus, the ITV pattern improves the power production under partial shading conditions and decreases the power losses when compared to other configurations.

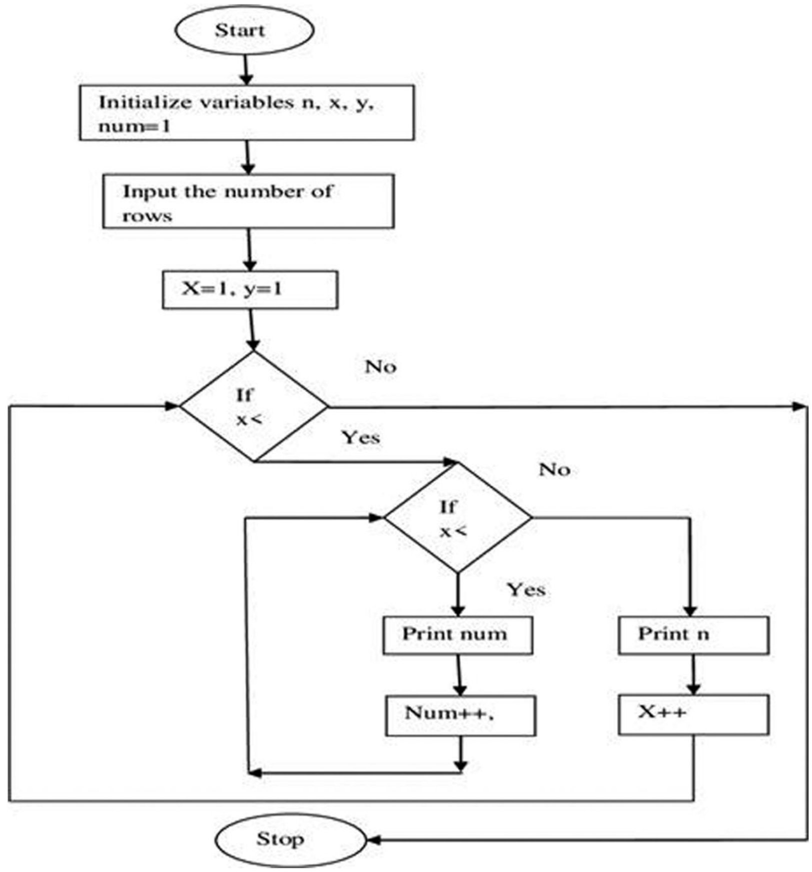

Figure 7: Algorithm and flowchart for TCT-ITV configuration

4 Simulation Results and Discussion

A 9 × 9 solar panel is interconnected in Total Cross Tied configuration and submitted to Large Wide shaded arrangement to estimate the operation of the proposed TCT-ITV method. The simulation is done for SDK, MSV and ITV-TCT pattern by MATLAB/Simulink environment. The outputs acquired are compared with MSV, SDK for the given shaded arrangement.

4.1 Long Wide Shade Pattern

A solar panel is separated into 5 various sets as per the irradiance level. First set gets an irradiance of 900 W/m^2, whereas the remaining gets 600 W/m^2, 500 W/m^2, 400 W/m^2, and 200 W/m^2 respectively and the shaded arrangement is displayed in Fig. 8. While whole column and most of row are submitted to shading, therefore, this shaded scheme is called as Long Wide. The array in row is in parallel connection. As a result, the maximum current produced is set by the addition of the current generated by particular cells.

4.2 SuDoKu Arrangement

A solar Panel with 5 several sets based on the irradiance level is taken in to account. The first set acquires an irradiance of 900W/m^2, where asother sets acquires 600 W/m^2, 500W/m^2, 400 W/m^2 and 200 W/m^2 respectively and the shaded arrangement is displayed in Fig. 9. The current in rows are estimated as if the 8^{th} and 9^{th} rows are bypassed, then the maximum power is generated from the solar. However, in SuDoKu arrangement, the peak power occurs resultant to the nominal voltage of the solar panel.

Furthermore, it can be supposed that the peak power generated by this configuration is 7870 W that is higher than that reached for Total Cross Tied arrangement.

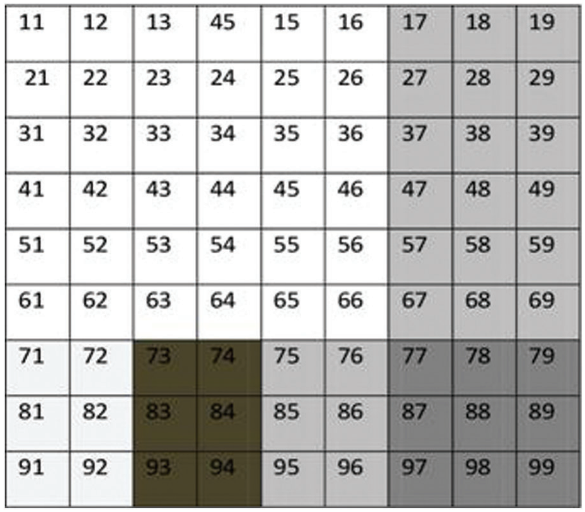

Figure 8: Long wide pattern using conventional TCT configuration

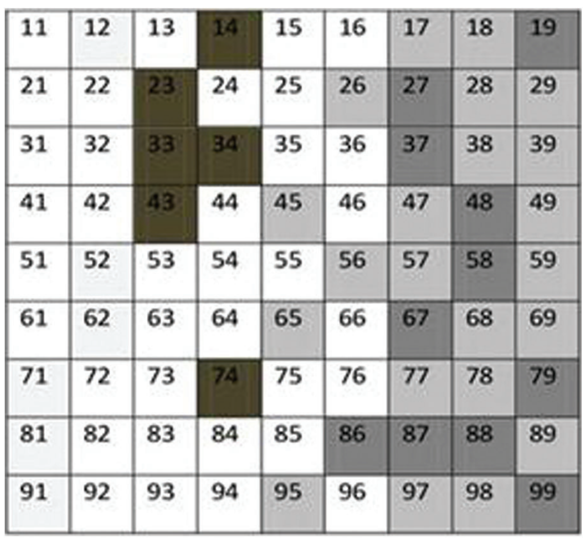

Figure 9: Shade dispersion using SDK scheme

4.3 Proposed ITV-TCT Configuration

The proposed technique is proven by the same 9 × 9 PV panel that is exposed to the considered shaded arrangement. The Shade dispersion using proposed ITV-TCT is shown in Fig. 10. The current in the nine rows are estimated below.

An uneven shadow pattern appears in photovoltaic systems. From 81 modules, 30 modules are shaded. The shade model consists of twelve modules with 700 W/m^2, fourteen modules with 400 W/m^2 and four modules with 200 W/m^2 at standard temperature. It is realized from Tab. 1 that for the **S**-ITV configuration local peak powers at 1428 W. The LP point corresponding to the lowest peak power of

1428 W is 137.9 V, 5.63 A. For this LP point, the PV system gives the maximum power of 3872 W and hence the LP point of the string is the GP point of the PV system. For the SP-ITV configuration local peak powers at 1476 W. The LP point corresponding to the lowest peak power of 1476 W is 136.7 V, 5.63 A. For this LP point, the PV system gives the maximum power of 3877 W and hence the LP point of the string is the GP point of the PV system. Fig. 11 shows the PV characteristics of S-ITV and SP-ITV.

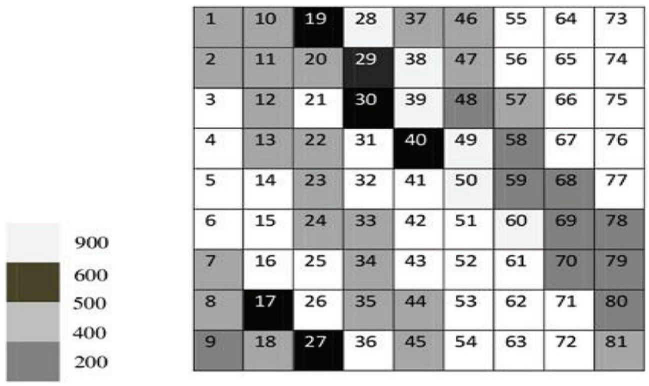

Figure 10: Shade dispersion using proposed ITV-TCT

Table 1: S-ITV and SP-ITV generated voltage, current and power of inner block shading

String No.	S-ITV				SP-ITV			
	Current (A)	Voltage (V)	LP Power (W)	PV system Maximum Power (W)	Current (A)	Voltage (V)	LP Power (W)	PV system Maximum Power (W)
1	5.63	136.2	1489	3421	5.63	135.8	1478	3521
2	5.63	137.9	1428	3782	5.63	136.7	1476	3511
3	7.26	159.36	1698	3766	7.60	163.36	1798	3760
4	7.26	152.17	1676	3723	7.56	154.17	1776	3720
5	7.26	142.79	1532	3673	6.80	146.79	1632	3672
6	7.59	151.3	1687	3760	7.60	155.3	1587	3760
7	6.23	140.6	1501	3652	6.21	146.6	1501	3652
8	8.21	172.1	1783	3872	8.11	175.3	1823	3874
9	8.01	170.12	1780	3871	8.11	172.12	1811	3877

For the configuration of SuDoKu is shown in Fig. 12a. In Fig. 12a, the current generated in each character string is described at this point. Ir6, Ir7 and Ir8 receive STC radiation. Therefore, the current generated is Ir6 = Ir6 = Ir8 = 63. The MSV configuration is shown in Fig. 12b. In Fig. 12b, the electricity generated in each string is described at this point. Ir5 = Ir6 receiving STC radiation. Therefore, the current generated is Ir5 = Ir6 = 51.68 A. For the TCT-ITV configuration shown in Fig. 12c, the currents generated in each string will be described at this stage. Ir5 = Ir6 receiving STC radiation. Therefore, the current generated is Ir5 = Ir6 = 51.68 A. From Tab. 2 it can be seen that the local peak power for the SuDoKu configuration is 1501 W. The LP point, which corresponds to the lowest peak power of 1501 W, is 16.23 V, 63.21 A. For this LP point, the PV system states a maximum power of 8093 W, and therefore the LP point is from the GP point string of the PV system. Fig. 13 shows the PV characteristics of SuDoKu, MSV and TCT-ITV. TCT-ITV proved to be the best. It is clear that the TCT-ITV model increases energy production from photovoltaic systems.

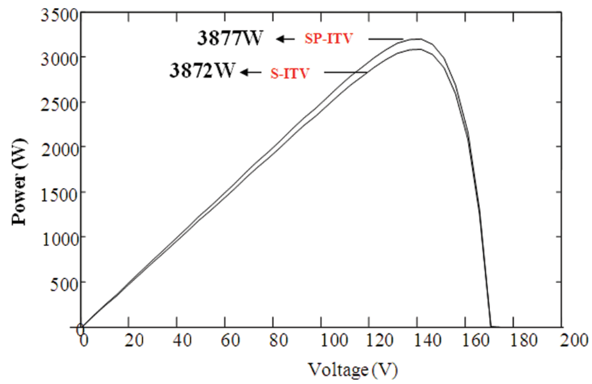

Figure 11: PV characteristics of S-ITV and SP-ITV

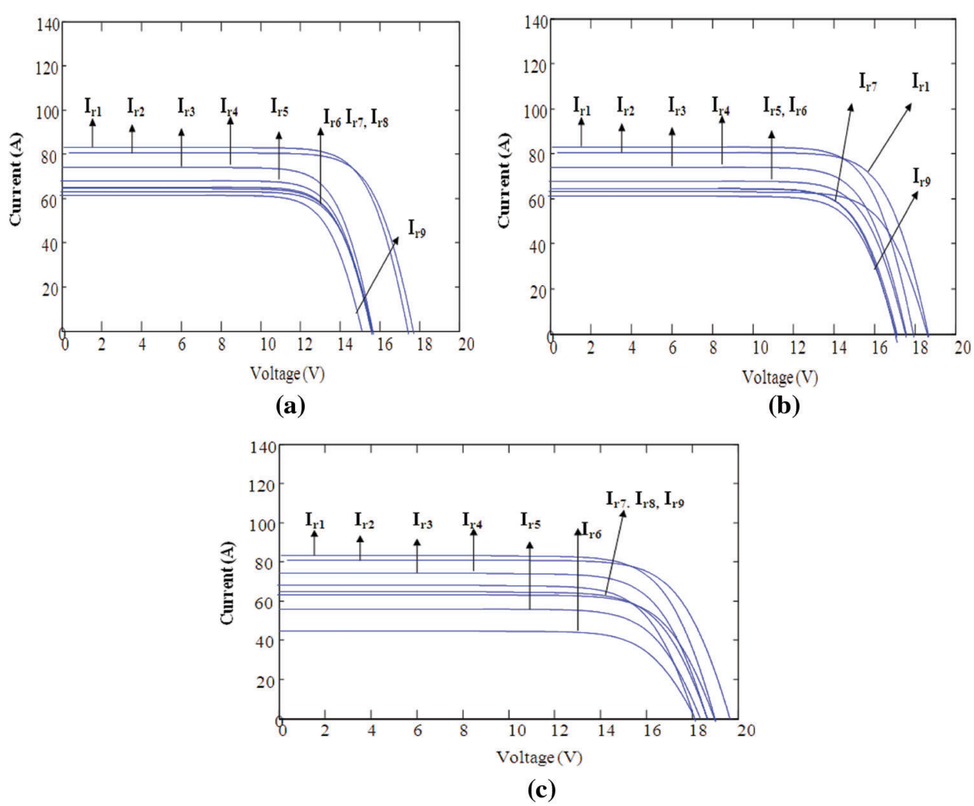

Figure 12: (a) SuDoKu (b) MSV and (c) TCT-ITV configurations

Table 2: SuDoKu, MSV, TCT-ITV generated voltage, current and Power of inner block shading

String No	SuDoKu				MSV				TCT-ITV			
	Current (A)	Voltage (V)	LP Power (W)	PV system Maximum Power (W)	Current (A)	Voltage (V)	LP Power (W)	PV system Maximum Power (W)	Current (A)	Voltage (V)	LP Power (W)	PV system Maximum Power (W)
1	73.78	16.67	1783	5261	74.78	18.67	1823	7261	75.78	19.67	3872	8093
2	63.11	16.63	1780	5252	62.21	18.21	1811	7252	63.21	19.21	3871	8062
3	61.32	16.12	1698	7221	61.48	18.12	1798	7321	61.23	19.12	3766	8061
4	61.21	16.02	1676	4782	61.56	18.02	1776	6782	61.87	19.02	3723	8042
5	56.62	15.87	1532	4791	51.68	17.87	1632	6791	50.62	18.87	3673	7987
6	63.21	15.13	1687	4711	51.68	17.32	1587	6711	40.2	18.32	3760	7981
7	63.21	16.23	1501	5198	68.21	18.03	1501	7198	73.21	19.03	3652	8021
8	63.21	16.11	1636	5162	70.21	18.12	1636	7162	72.21	19.32	3711	8032
9	70.67	16.62	1599	5122	71.67	18.32	1599	7122	70.67	19.3	3698	8030

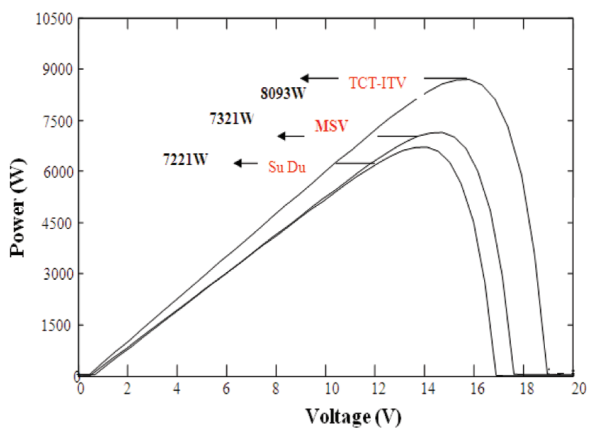

Figure 13: PV characteristics of SuDoKu, MSV and TCT-ITV

For the local SP-ITV peak power configuration at 1501 W. The LP point, which corresponds to the lowest peak power of 1501 W, is 146.6 V, 7.60 A. The PV system provides a maximum output for this LP point of 7331 W, and therefore the LP point of the string is the GP point of the PV system.

Tab. 3 provides the current, voltage and power of the proposed system with conventional configuration. It is observed that the proposed configuration provides more output than the other conventional configuration.

Table 3: Comparison results of various configurations

	S-ITV	SP-ITV	SuDoKu	MSV	Proposed TCT-ITV
Current (A)	40.122	58.06	64.74	76.09	83.69
Voltage (V)	14.7	15.1	16.6	18.5	19.8
Power (W)	5890	6570	7870	8621	9765

Figs. 14 and 15 displays the output voltage and current due to various irradiations for different connections. The Proposed Inverted Triangle configuration provides more output results than the conventional configuration. Fig. 16 shows the power relations of Proposed and conventional methods.

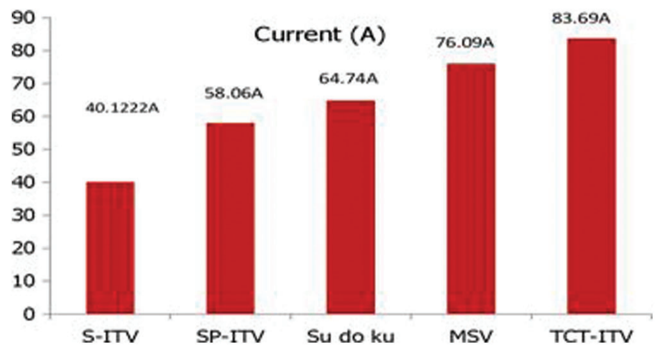

Figure 14: Current output due to various configurations

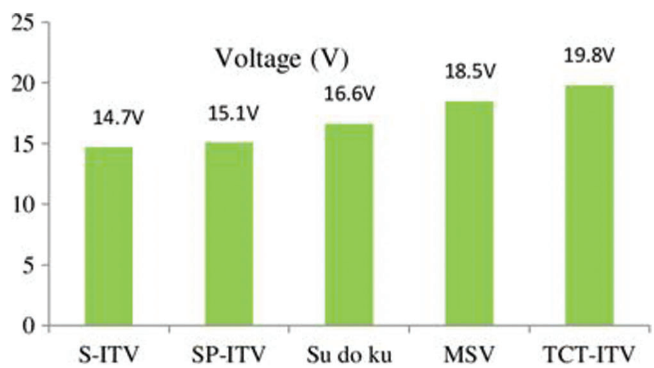

Figure 15: Voltage output due to various configurations

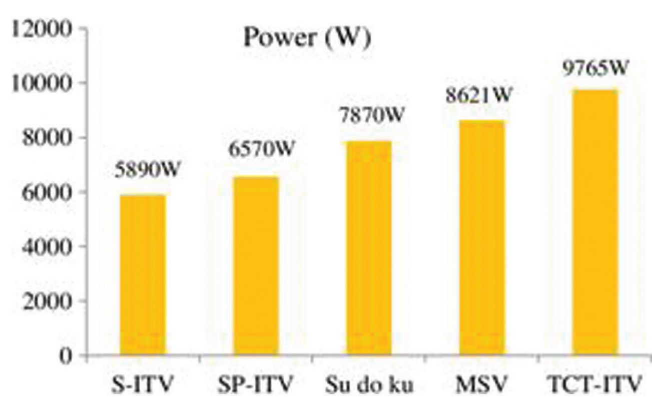

Figure 16: Power output due to various configurations

It is observed that by the TCT-ITV configuration, the PV system maximum power generation is 66,000 watts, which is higher than that of the TCT configuration. It can be seen in Tab. 4, the proposed

ITV-TCT configuration has higher power enhancement than the conventional configurations such as SDK, CDV and MSV.

Table 4: Comparison of power enhancement in proposed and conventional configurations

Maximum power	Configuration structure	Power enhancement
Indu Rani et al. (2013)	SuDoKu	3.6
John Bosco (2017)	CDV-TCT	6.38
Lahuen El (2018)	MSV	7.12
Proposed system	ITV-TCT	7.89

5 Conclusion

The simulation of 9 × 9 solar PV modules under various shading patterns with degrees of shading are performed based on Matlab/Simulink. The three standard configurations of solar PV array consisting of series (s), series-parallel (SP) and total cross-tied (TCT), recently developed SuDoKu, magic square view configuration are studied. This paper proposes ITV configuration for the arrangement of PV modules in a PV array which exhibits an improvement in PV power generation under partially shaded. The ITV configuration spreads the effect of shading over the entire PV modules and decreases the mismatch losses of modules thereby improving the produced PV power. The performance of the system is analyzed, and it is proved that the proposed technique allows better results as compared to conventional schemes. It is observed that by the TCT-ITV configuration, the PV system maximum power generation is 66,000 watts, which is higher than that of the existing topologies available in the literatures such as S, SP and TCT configuration.

Acknowledgement: The authors with a deep sense of gratitude would thank the supervisor for his guidance and constant support rendered during this research.

Funding Statement: The authors received no specific funding for this study.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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