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http://www.ijert.org
International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 13 Issue 9, September 2024

Investigating the Impact of Solar Photovoltaic Array Size on its Performance under Partially Shaded Conditions using Lambert W-Function

Niti Agrawal
Department of Physics, Shyamlal College, University of Delhi, Delhi-110032, India

***Abstract*—This Photovoltaic (PV) system displays reduction in the output power and efficiency under partial shading conditions (PSCs). The losses incurred due to partial shading strongly depends on the shading pattern, extent of the shade, size and configuration of the PV array. The aim of this paper is to investigate the effect of array size on the output performance of partially shaded PV arrays having different configuration. For this purpose, two different configurations of PV array namely, series-parallel (SP) and total-cross-tied (TCT) of seven different sizes (three for symmetric array and four for asymmetric array) have been considered. The output performances of the PV arrays of different sizes have been simulated using a method based on Lambert W-function, which is a well-established method to tackle transcendental current-voltage relation of a solar cell / module. The conclusions are derived based on the obtained values of maximum output power, power loss due to PS, fill factor and efficiency.**

***Keywords*— Photovoltaics; Partial shading; Lambert W-function; Total-cross-Tied; Series-parallel; Power loss;**

I. INTRODUCTION

This Solar photovoltaic (PV) has emerged as the potential replacement of the conventional energy resources owing to their abundance and green nature. However, partial shading (PS) is a phenomenon that adversely impacts the efficiency and capacity of a PV system to generate maximum power [1,2]. This is a common condition which occurs because of the shade created by the nearby building, structures, trees, moving cloud, accumulation of debris etc resulting in non-uniform distribution of solar irradiance over PV surface. This mismatch makes output I-V and P-V characteristics of a PV system under PS complex with appearance of multiple Maximum Power Point (MPP), resulting in power loss [3-5].

Impact of partial shading conditions (PSCs) on the output of PV system has been an active area of research. Different methods have been used by the researchers to simulate the complex characteristics of PV array under PSCs such as numerically solving the system of equation [6], using Newton Raphson method to model the behaviour of PV field [7], solving the simultaneous nonlinear equations [8], using artificial neural network (ANN) based methodology [9] to detect and assess partial shading conditions in PV array. However, these methods are computationally complex and convergence can become an issue when obtaining numerical solution for large system of equations.

These problems can primarily be attributed to the fact that current-voltage relation of the basic PV cell is transcendental in nature. Hence it is not possible to solve it for current as a function of voltage explicitly and vice versa [10]. Lambert W function W{x} is a mathematical function defined as the inverse of the equation $W.e^{W} = x$. Using Lambert W function the solution of the transcendental current-voltage relation of a PV cell or PV module can be obtained explicitly [11]. Lambert W function has been used by many researchers in their studies e.g., Cubas et al., determined the explicit expression for equivalent circuit parameters of solar panel [12], Bastidas et al., modelled the Series-Parallel (SP) configuration of PV arrays in mismatching conditions [13], Fathabadi though using the Lambert W function based tracked the MPP of PV modules connected in Series, parallel and SP configuration, but didn't consider PSCs [14], Batzelis and Routsolias used Lambert W function to form an efficient explicit model of PV string i.e., only series configuration of PV array [15].

In an attempt to minimize power loss under PSCs, different other configurations of PV arrays can also be found in the literature such as total cross tied (TCT), honey comb (HC), bridge linked (BL), hybrid, mathematical puzzle based configuration [16]-[21]. Study and implementation of different configuration is gaining importance because under PSC their output performance is different, unlike uniform irradiation condition where output performance of different configurations is similar. However, study of different configurations under PSC using Lambert W function is still required. A comparison between purely series and purely parallel configurations under PSC using Lambert W function was presented in [22]. Recently, the author presented a technique based on Lambert W function to simulate and compare the output performance of SP and TCT configured PV array under PSCs [23]. The effect of different shading patterns on both the configurations of a constant size has been studied. In the present paper, the using the same methodology, the role of array size on its output performance under PSC is investigated. The output performance of seven different sized arrays of both SP and TCT configurations under same specific shadow pattern is studied. Comparative analysis for SP and TCT configuration is presented thereafter.

International Journal of Engineering Research & Technology (IJERT)
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II. ELECTRICAL MODEL OF A PV MODULE USING LAMBERT W-FUNCTION

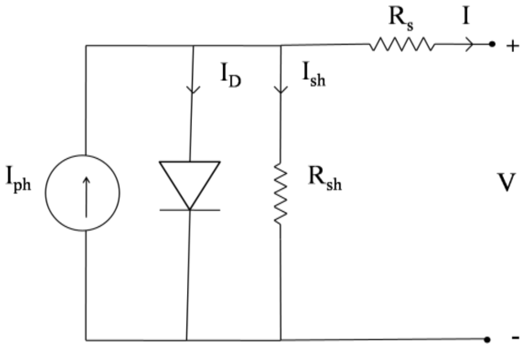

Fig.1 Representation of a solar cell using single diode model.

A PV cell is the fundamental PV unit, which is commonly modelled using single diode model (Fig.1) [24],[25]. Using this model, the electrical characteristic of a PV module which has N_s solar cells in series is attained by Eq. (1) [13].

$$I_m = I_{ph} - I_o \left[exp\left(\frac{V_m + I_m R_s N_s}{nV_{th} N_s}\right) - 1\right] - \left(\frac{V_m + I_m R_s N_s}{R_{sh} N_s}\right) \quad (1)$$

where I_m and V_m are the output current and output voltage of PV module, I_{ph} is the photo generated current, I_o is the reverse saturation current, R_s and R_{sh} represents the series and shunt resistances of single solar cell of the PV module, n is the diode ideality factor, $V_{th} = (kT/q)$, is the thermal voltage of the solar cell, T is the temperature in Kelvin, k is the Boltzmann's constant, q is the fundamental charge.

The output current-voltage equation of PV module is obtained explicitly using Lambert W-function is given by Eq. (2).

$$V_m = I_o R_{sh} N_s + I_{ph} R_{sh} N_s - I_m R_s N_s - I_m R_{sh} N_s$$

$$-nN_s V_{th} LambertW \quad \frac{R_{sh} I_o}{nV_{th}} \quad e^{\frac{(I_o + I_{ph} - I_m) R_{sh}}{n N_s V_{th}}} \quad (2)$$

The photo current generated by the module at any temperature T and solar irradiation G, is obtained using Eq. (3) [24].

$$I_{ph} = [I_{phn} + K_I (T - T_n)] \left(\frac{G}{G_n}\right) \quad (3)$$

Where I_{phn} is the photo current generated by the module at STC conditions, K_I is the temperature coefficient of short circuit current (A/K), T_n and G_n are the module temperatures and solar irradiance at STC, respectively.

The short circuit current of the PV module is given by Eq. (4).

$$I_{sc} = \frac{R_{sh}(I_o + I_{ph})}{R_s + R_{sh}} - \frac{(n V_{th})}{R_s}$$

$$Lambert\ W \left[\frac{R_{sh} I_o R_s N_s}{(R_s + R_{sh}) n N_s V_{th}} \ exp \left[\frac{R_{sh}(R_s I_o N_s + R_s I_{ph} N_s}{(R_s + R_{sh}) n N_s V_{th}} \right.\right. \quad (4)$$

III. METHODOLOGY

Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

A. PV array configurations

Two configurations of PV array namely, Series-Parallel (SP) and Total Cross Tied (TCT) have been used in this study. A brief description of the configurations is given below:

- Series-Parallel (SP) PV array configuration

Series-parallel configuration of the PV array is the one where PV modules are first connected in series to constitute a series string. Many such strings are then connected in parallel (Fig.2.a). For such a configuration, array current (I_a) is given by the addition of currents of individual strings and array voltage (V_a) is same as the voltage across any string.

$$I_a = \sum I_{str} \quad (7a)$$

$$V_a = V_{str} \quad (7b)$$

- Total-cross-tied (TCT) PV array configuration

Total cross tied array configuration is a modification of series-parallel configuration (Fig. 2.b.). By connecting ties across each row of junction, TCT configuration is formed [16]. In this configuration all the modules present in a single row are connected in parallel with each other. Many such rows are then interconnected in series to constitute TCT configuration. Here, the PV array current is same as any row current, while the array voltage is obtained by adding voltages across each row.

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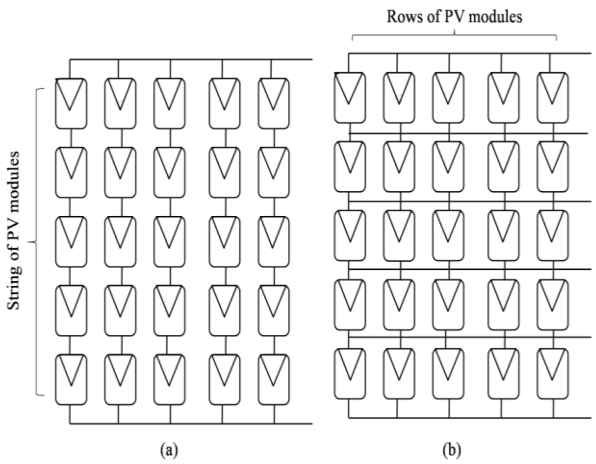

Fig. 2. Diagrammatic representation of PV array configurations (a) SP (b) TCT

$$I_a = I_{row} \tag{8a}$$

$$V_a = \sum V_{row} \tag{8b}$$

B. Simulation of output characteristics of PV arrays

The output characteristics of SP and TCT PV array configuration are simulated using a program based on Lambert W function. The flow chart of the program to simulate SP and TCT PV array is presented in Fig. 3 and Fig. 4 respectively. The program is based on determining explicitly I-V relation for each PV module using Lambert W-function. PV module is modelled using single diode model with series and shunt resistances. Linear interpolation is thereafter used to sum up currents and/or voltages to simulate the I-V and P-V characteristics for the entire array. Further details of the program are present in author's earlier work [23]. For this work parameters of KYOCERA KC200GT PV module has been used.

C. Array sizes and shading pattern

To study the role of array size on its output performance, SP and TCT PV arrays, each of seven different sizes 3x3, 4x3, 5x3, 3x4, 5x3, 4x4, 5x5 (Fig.5) have been considered for this investigation. Taking 3x3 as the base size, array is extended asymmetrically by adding only columns (3x4, 3x5) and then only rows (4x3, 5x3). The basic array is also extended symmetrically by adding both columns and rows simultaneously (4x4, 5x5). All the different sized arrays have been considered to be under the impact of a constant square shaped shading pattern covering four modules.

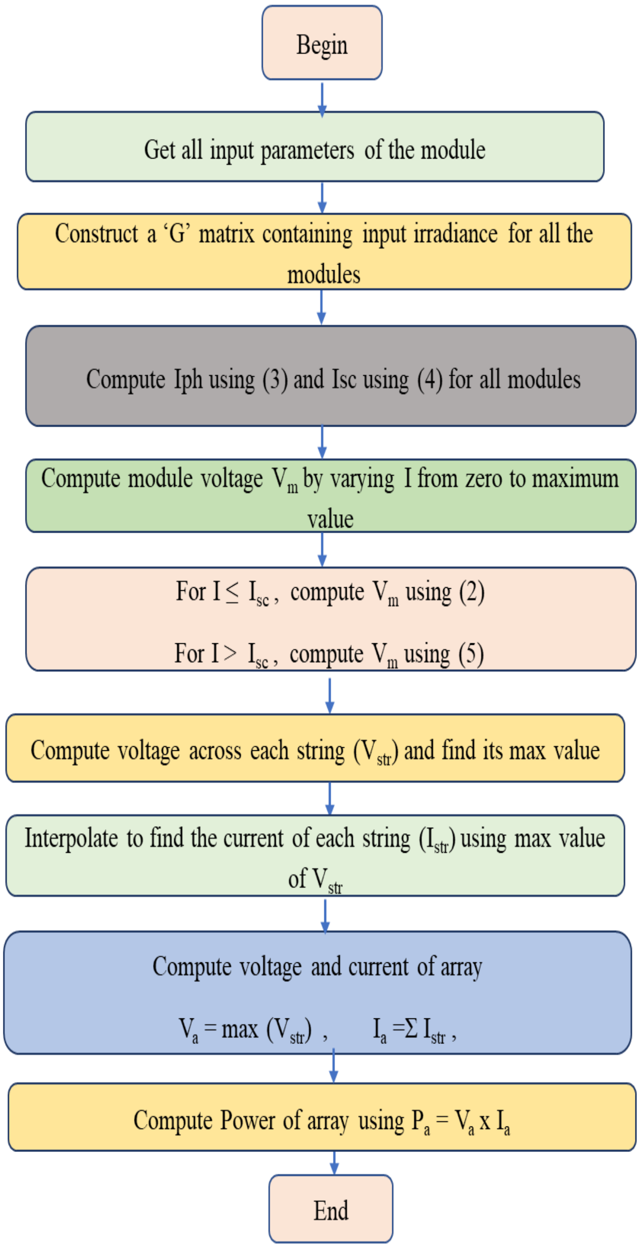

Fig. 3 Flowchart for the simulation of SP PV array.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 13 Issue 9, September 2024

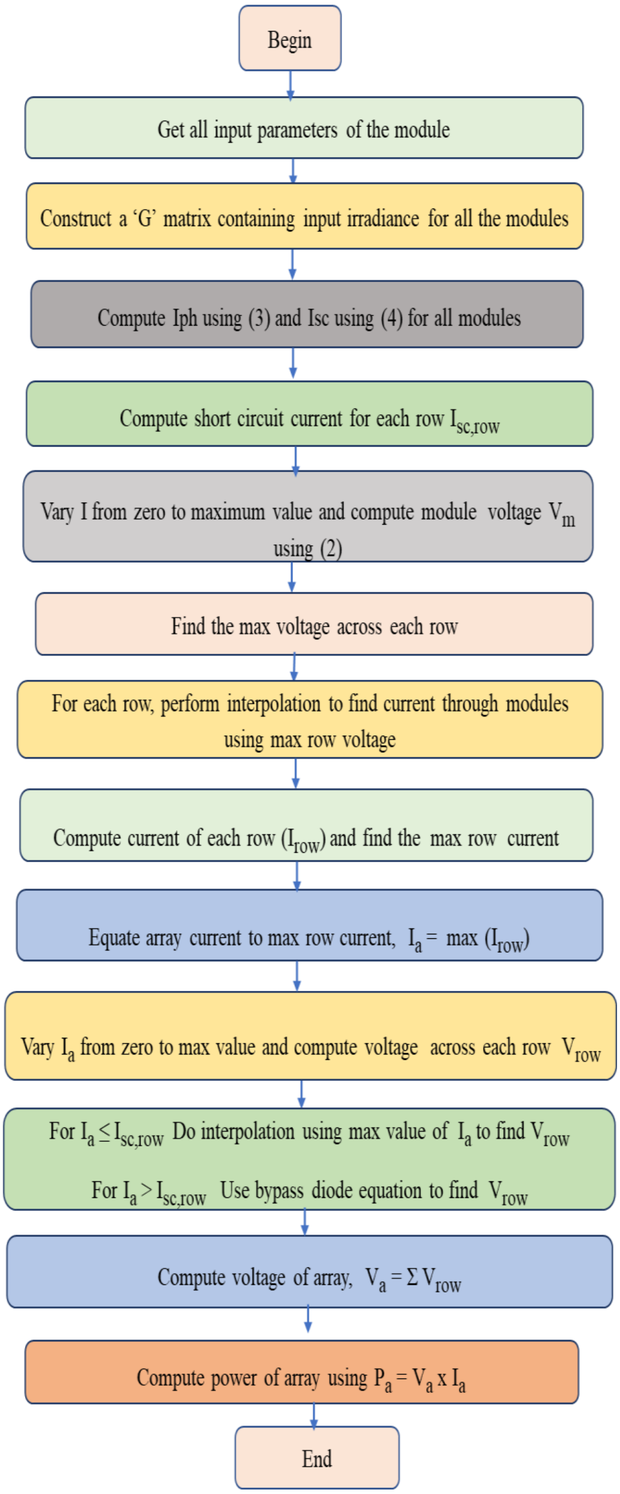

Fig. 4 Flowchart for the simulation of TCT PV array.

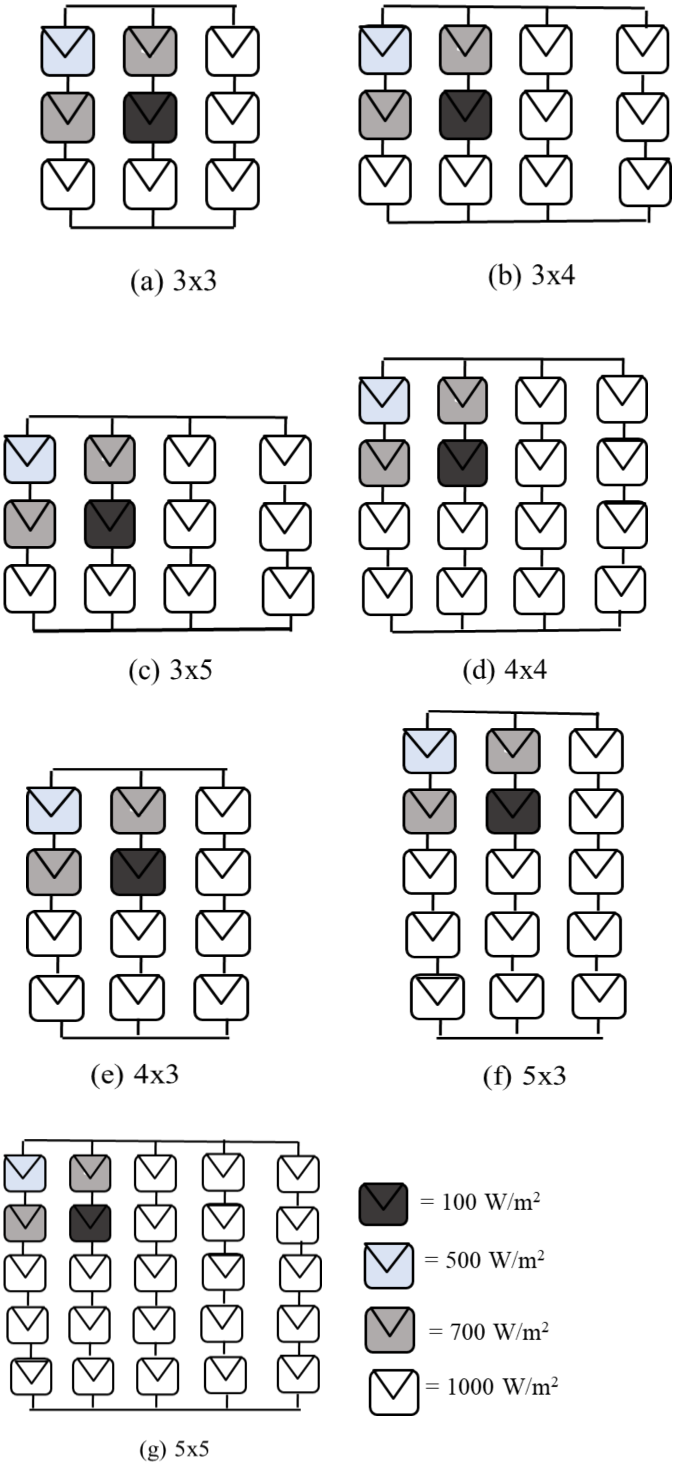

Fig. 5 Different array sizes with same shading pattern.

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International Journal of Engineering Research & Technology (IJERT)
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D. Performance analysis of SP and TCT configured PV array

The output performance of SP and TCT configured PV arrays of different sizes under partial shading conditions have been estimated in terms of maximum output power, power loss, efficiency and fill factor. These parameters are defined below:

The power loss (ΔP) of the PV array under partial shading is given by Eq. (9).

$$\Delta P(\%) = \left(\frac{P_{max} - P_{m\_shd}}{P_{max}}\right) \times 100 \quad (9)$$

Where P_{max} is the maximum power generated by the PV array under uniform irradiance of 1000 W/m^2 and P_{m_shd} is the maximum power generated by the same array under partial shading condition.

Fill factor (FF) is a parameter which is indicative of PV array performance. Fill factor is defined by Eq. (10).

$$FF = \frac{V_{mp} \times I_{mp}}{V_{OC} \times I_{SC}} \quad (10)$$

where V_{mp} is the voltage at which maximum power is obtained, I_{mp} is the current at maximum power point, V_{oc} represents the open circuit voltage and I_{sc} is the short circuit current of the PV array.

Efficiency (η) is the ratio of the maximum output power generated by the PV array to the input solar power and is calculated using Eq. (11).

$$\eta = \frac{V_{mp} \times I_{mp}}{E \times A} \times 100 \quad (11)$$

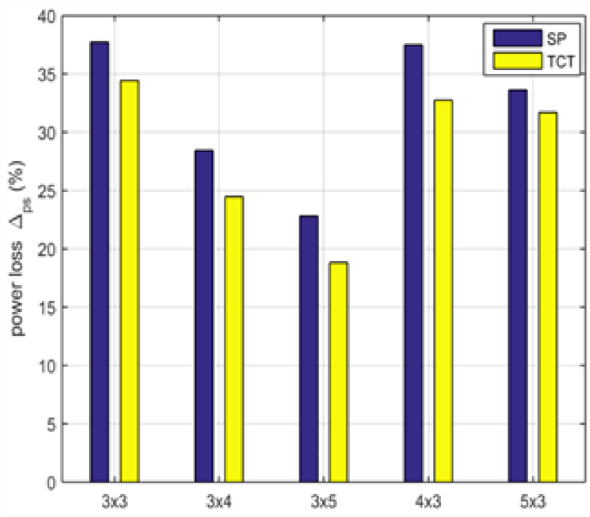
Where 'E' is the input solar irradiance per unit area (W/m^2) and 'A' is the area of the PV array on which it falls.

IV. RESULTS AND DISCUSSION

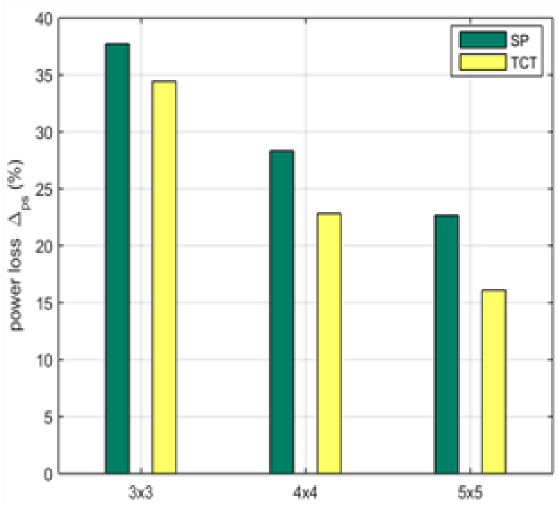
The simulated result for different sizes of SP and TCT PV array is presented in Table I. The results clearly show that for all array sizes under same shading pattern, TCT configured PV array output performance excels over SP array. 3X3 TCT array generates 1180.0 W while 3X3 SP array generates lesser power of 1120.9 W. It is observed that impact of adding columns on the output performance of asymmetric arrays is different from adding same number of rows. In case of asymmetric TCT configured array, addition of two columns increases the output power by 1255.1 W (106.4%) whereas by adding two rows output power generated increases by 869.5 W (73.7%). In case of asymmetric SP array under same shading pattern, addition of two columns increases the output power by 1195.2 W (106.6%) whereas addition of two rows increase output power by 870.9 W (77.7%). For a symmetric TCT configured array, increasing its size from 3x3 to 5x5 under same shading pattern increases the maximum power by 3014.1 W whereas in case of array with SP configuration increase of 2745.5 W in the maximum output power is obtained.

TABLE I. SIMULATED VALUES OF VARIOUS PARAMETERS OF SP AND TCT ARRAY CONFIGURATION UNDER SHADED CONDITION.

	PV Array Configuration					
	SP			TCT		
Array size	***Max. Power (W)***	***η***	***FF***	***Max. Power (W)***	***η***	***FF***
3x3	1120.9	11.33	0.47	1180.1	11.92	0.49
3x4	1717.4	12.14	0.54	1812.9	12.82	0.57
3x5	2316.1	12.58	0.58	2435.2	13.25	0.61
4x3	1499.9	10.60	0.47	1614.0	11.41	0.50
5x3	1991.8	10.83	0.50	2049.6	11.15	0.51
4x4	2293.5	11.59	0.54	2469.9	12.48	0.58
5x5	3866.4	11.89	0.58	4194.2	12.90	0.62



(a)



(b)

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Fig.6 Variation of partial shading power loss with array size for SP and TCT (a) asymmetric (b) symmetric configured arrays under constant shading pattern.

International Journal of Engineering Research & Technology (IJERT)
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The efficiency of the PV array also increases by adding columns than rows. For TCT array, efficiency of 3X5 array is 13.25% while for 5X3 it is lesser (11.15%). For SP array, efficiency of 3X5 array is 12.58% while for 5X3 it is 10.83%.
Variation of partial shading power loss with array size is presented in Fig. 6, which clearly demonstrates that the decrease in power loss under constant shading pattern with increase in array size is found more in TCT configuration than SP.

V. CONCLUSIONS

In this study the impact of array size on the performance of partially shaded PV array has been investigated. Under constant shading pattern, power generation capability and power loss of a PV array depends on the size and configuration of the array. Both symmetrical (3x3, 4x4, 5x5) and asymmetrical (3x4, 3x5, 5x3, 4x3) arrays were used for the analysis. It is observed that in general as the size of the array increases, partial shading power loss decreases when the shading pattern and size is kept constant. However, for asymmetrical arrays, it is observed that adding more numbers of columns reduce the partial shading power loss more than adding same number of rows. In general, under complex non uniform irradiance, mitigation of power loss and performance enhancement of PV system can be achieved by using TCT configured PV array over SP. The insight given by this research work will add to the development of power losses minimization technique development.

REFERENCES

[1] H. Patel, V. Agarwal, "MATLAB based modelling to study the effects of partial shading on PV array characteristics," IEEE Trans. on Energy Conversion, vol. 23 (1), pp 302-310, 2008.

[2] S.R. Pendem, S. Mikkili, "Modelling and performance assessment of PV array topologies under partial shading conditions to mitigate the mismatching power losses," Solar Energy, Vol. 160, pp 303-32, 20018.

[3] M.S. Palanisamy, P.W. David, P. Murugesan, H. Thangaraj, "A novel Global maximum power extraction technique for partial shaded solar PV system," Energy Conversion and Management, Vol. 313, 2024, Article No.118595, 2024. https://doi.org/10.1016/j.enconman.2024.118595

[4] K. Lappalainen, S. Valkealahti, "Photovoltaic mismatch losses caused by moving clouds," Solar Energy, Vol. 158, pp 455-461, 2017.

[5] M.R. Maghami, H. Hizam, C. Gomes, M.A. Radzi, M.I. Rezadad, S. Hajighorbani, "Power loss due to soiling on solar panel: A review," Renewable and Sustainable Energy Reviews, Vol. 59, pp 1307-1316, 2016.

[6] V. Quaschning, R. Hanitsch, "Numerical simulation of current-voltage characteristics of photovoltaic systems with shaded solar cells," Solar Energy, Vol. 56 (6), pp 513-520, 1996.

[7] G. Petrone, C.A. Ramos Paja, "Modelling of photovoltaic fields in mismatched conditions for energy yield evaluation," Electric Power Sytems Research, Vol. 81, pp 1003-1013, 2011.

[8] Y.J. Hsu, P.C. Hsu, "An investigation on partial shading of PV modules with different connection configurations of PV cells," Energy, Vol. 36, pp 3069–3078, 2011.

[9] F. Salem, M.A. Awadallah, "Detection and assessment of partial shading in photovoltaic arrays," Journal of Electrical Systems and Information Technology, Vol. 3(1), pp 23-32, 2016.

[10] A. Shaheen, A. Ginidi, "Electrical parameters extraction of PV modules using artificial hummingbird optimizer," Scientific Reports, Vol.13(1), pp 1-23, 2023. https://doi.org/10.1038/s41598-023-36284-0.

[11] A. Jain, A. Kapoor, "Exact analytical solutions of the parameters of real solar cells using Lambert W-function," Solar Energy Materials and Solar Cells, vol. 85, pp 391–396, 2005.

[12] J. Cubas, S. Pindado, M, Victoria, "On the analytical approach for modeling photovoltaic systems behavior," Journal of Power Sources, Vol. 247, pp 467-474, 2014.

[13] J.D. Bastidas, E. Franco, G. Petrone, C.A. Ramos-Paja, G. Spagnuolo, "A model of photovoltaic fields in mismatching conditions featuring and improve calculation speed," Electric Power Systems Research, vol. 96, pp 81-90, 2013

[14] H. Fathabadi, "Lambert W function based technique for tracking the maximum power point of PV modules connected in various configuration," Renewable Energy, vol. 74, pp 214-226, 2015.

[15] E.I. Batzelis, I.A. Routsolias, "An explicit PV string model based on Lambert W function and simplified MPP expressions for operation under partial shading," IEEE transactions on Sustainable energy, vol. 5, No.1, pp 301-312, 2014.

[16] N.D. Kaushika, N.K. Gautam, "Energy yield simulations of interconnected solar PV arrays," IEEE Transactions on Energy Conversion, Vol. 18, No. 1, pp 127-133, 2003.

[17] R. Ramaprabha, B.L. Mathur, "A comprehensive review and analysis of solar photovoltaic array configurations under partial shaded condition," International Journal of Photoenergy. Vol 2012, Article ID 120214, 16 pages doi:10.1155/2012/120214.

[18] G. Sagar, D. Pathak, P. Gaur, V. Jain, "A Su Do Ku puzzle based shade dispersion for maximum power enhancement of partially shaded hybrid bridge-link-total-cross-tied PV array," Solar Energy, Vol. 204, pp. 161–180, 2020. doi: 10.1016/j.solener.2020.04.054.

[19] A.S. Yadav, R.K. Pachauri, Y. K. Chauhan, S. Choudhury, R. Singh, "Performance enhancement of partially shaded PV array using novel shade dispersion effect on magic square puzzle configuration," Solar Energy, Vol. 144, pp 780-797, 2017.

[20] N. Agrawal, B. Bora, S. Rai, A. Kapoor, M. Gupta, "Performance Enhancement by Novel Hybrid PV Array Without and With Bypass Diode Under Partial Shaded Conditions: An Experimental Study," International journal of renewable energy research, vol. 11, No. 4, pp 1881-1891, 2021.

[21] N. Agrawal, B. Bora, A. Kapoor, "Experimental investigations of fault tolerance due to shading in photovoltaic modules with different interconnected solar cell networks," Solar Energy, Vol. 211, pp 1239-1254, 2020.

[22] N. Argawal, A. Kapoor, "Investigation of the effect of partial shading on series and parallel connected solar photovoltaic modules using Lambert W-function," AIP Conf. Proc.2006,030050-1-030050-5; https://doi.org/10.1063/1.5051306.

[23] N. Agrawal, "Lambert W function-based technique to estimate and compare the performance of partially shaded series-parallel and total-cross-tied configured PV array," Renewable Energy Research and Applications, 2024, doi: 10.22044/rera.2024.13624.1251 (In Press)

[24] M.G. Villalva, "Comprehensive approach to modelling and simulation of photovoltaic arrays," IEEE Trans. Power Electron. Vol. 24, pp 1198-1208, 2009.

[25] S.C. Ezike, J. B. Yerima, D. William, B. Alkali, A.D. Ahmed, "Extraction of Five Photovoltaic Parameters of Nature-based Dye-Sensitized Solar Cells using Single Diode Model," Renewable Energy Research and Applications, Vol. 4(2), pp 199-208, 2023. doi: 10.22044/rera.2022.12062.1151