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Abstract. In order to fight climate change, investors, policy-makers, and power producers around the world are focusing on decreasing the share of generation from fossil fuels and increasing the share of renewable energy generation, especially through harnessing abundantly available solar energy. However, the power output and reliability of the photovoltaic (PV) plants are affected due to partial shading to a great extent. This paper investigates the effect of increasing the interconnection redundancy in the PV array in mitigative the power loss under different partial shading conditions in MATLAB® platform. The analysis revealed that the configuration with no interconnection redundancy (i.e., a series-parallel array) and with fill redundancy (i.e., a total cross-tied array) performs equally well under uniform irradiance and under self-shading created by low altitude sun, e.g., during sunrise and sunset, when the distance between adjacent rows is inadequate. In case of all other shading scenarios, such as shading created by nearby buildings, trees, poles, and non-uniform dust accumulation, an increase in the interconnection redundancy increases the performance ratio of the PV plant.

Keywords: Modeling and Simulation, Partial shading, Photovoltaics, PV array topology.

1 Introduction

The economic development of any country has a direct correlation with the quality and quantity of energy supply [1], but at the same time, the choice of energy resource plays a very crucial role in ensuring environmental sustainability [2]-[4]. Presently due to the global environmental crisis, globally there is a conscious effort to reduce the share of electricity generation from coal and other polluting fossil fuel and increase the use of solar energy, which is the most abundantly available clean energy resource [5] - [10]. However, solar energy has several inherent challenges [11], which impact its performance and as well as its reliability [12]; partial shading is one of those [13]. But most of the past studies revolve around the issue of enhancement of power output using different photo-responsive materials [14], [15], and the issues of decline in output power and reliability due to partial shading conditions (PSC) have not been paid equal attention [16], [17]. Few methods have been developed to reduce the mismatch losses under PSC, such as multilevel converters [18], parallel connection of module [19], and micro converters [20], but a common downside among all these methods is the requirement of a large number of equipment, the increase in cost thereof, and the complexity of the algorithms [6],[7].

In this paper, a comparative study is presented on the performance of TCT configuration and conventional Series Parallel under different partial shading conditions. To investigate the performance of these two array configurations under different real-world scenarios of partial shading, in the present work, six shading patterns are simulated in MATLAB on a 3×3 PV array.

After this brief introduction, the rest of the paper is organized as follows. The modeling and simulation of PV cells are discussed in Section 2. In which the simulated shading modes and irradiance patterns are also delineated. Section 3 presents the results and discussion, followed by Section 4, which summarizes the main conclusions of the present work.

2 Modelling and Simulation

2.1 Modeling of PV Cell

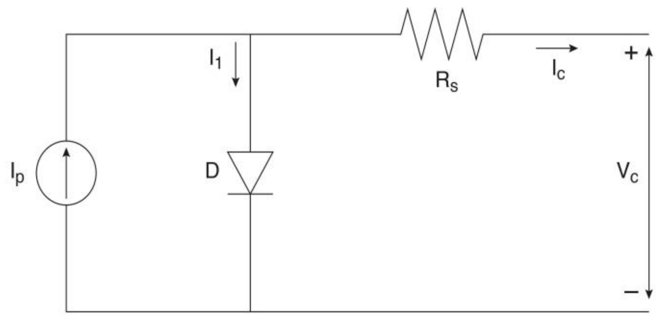


Fig. 1. Single diode equivalent circuit model of a PV cell.

An equivalent circuit diagram of PV cells is shown in Fig. 1, and the output current of the cell, *i.e.*, I_c may be quantified by Eq. (1) [13]. Here, I_p symbolizes photocurrent (i.e., current source), D denotes diode, Z denotes diode ideality factor, K symbolizes Boltzmann's constant, e is electron charge, while T and I_{sat} are temperature in °C, and saturation current, respectively.

$$I_c = I_p - I_{sat} \times \left(\frac{e(V_c+I_cR_s)}{zkT} - 1\right) \quad (1)$$

T_{op} denotes the operating temperature of a solar cell that depends on the solar irradiation level S_1. This is shown using Eq. (2) [13].

$$C_{Tg} = T \times (T_h - T_b) + 1 \quad \& \quad C_{Tg} = \frac{T\times(T_h-T_b)}{S_1}+1 \quad (2)$$

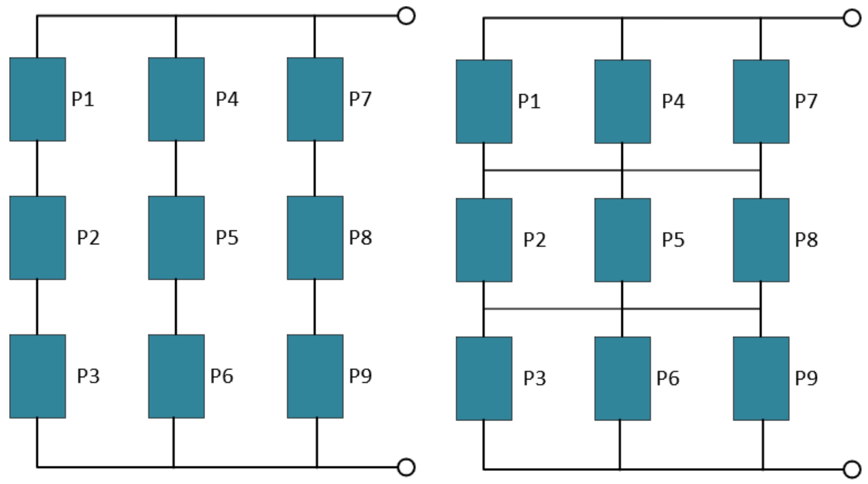
The effect of S_{ir}, the irradiation level on the voltage and photocurrent can be evaluated with the assistance of correction factors C_{Ss} and C_{So} as Eq. (3) [13].

$$C_{Ss} = T_S \times (S_{ir} - S_1) + 1, \quad C_{So} = \left(\frac{1}{S_1}\right) \times (S_{ir} - S_1) + 1 \tag{3}$$

S_1 and S_{ir} are the reference and insolation level, respectively.

2.2 The PV array and Shading modes

For investigating the relative performance of the series-parallel (SP) and total cross-ties (TCT) arrays, in the present work, a 3×3 matrix of PV modules is modeled in the MATLAB platform (see Fig. 2). In a real-world scenario, the PV arrays may be subjected to different shading conditions due to various environmental reasons, such as moving clouds, non-uniform dust accumulation over the panels, bird droppings, shading from nearby buildings, poles, trees, and other structures. To simulate these probable real-world scenarios, six different Cases are considered in the present study (see Table 1). The relative performances of both SP and TCT configurations are studied under these shading cases, and the result of the same is presented in Section 3.



(a) **(b)**

Fig. 2. PV configurations (a) Series-parallel and (b) total cross-tied.

3 Results and discussion

The P-V characteristics obtained under different shading conditions (see Table 1) are presented in Figs. 5 - 10. The exhibited P-V characteristics compare the results of the TCT circuit and the conventional series-parallel configuration. Tables 2 and 3 present the performance parameters (*Pmax*, *Vmpp*, *Impp*) under different shading scenarios for the simulated circuits.

Table 1. Considered patterns and intensities over different modules of the array

	Irradiance, W/m2								
	P1	P2	P3	P4	P5	P6	P7	P8	P9
Case-1	1000	1000	1000	1000	1000	1000	1000	1000	1000
Case-2	400	600	200	1000	1000	1000	1000	1000	1000
Case-3	400	600	200	300	300	500	1000	1000	1000
Case-4	800	600	200	800	800	1000	200	1000	1000
Case-5	600	1000	1000	300	1000	1000	800	1000	1000
Case-6	500	300	1000	400	400	1000	300	500	1000

For Case-1, i.e., without shading scenarios (see Fig.3), the PV curves superimpose each other, and no difference could be found between SP and TCT arrays, which implies that both SP and TCT produce the same power under uniform irradiance condition. Cases 2 and 3, i.e., for vertical shading scenario, TCT shows better responses than SP and produces more power output (see Figs. 4 and 5). The multiple maxima may be observed in both of these cases due to partial shading conditions.

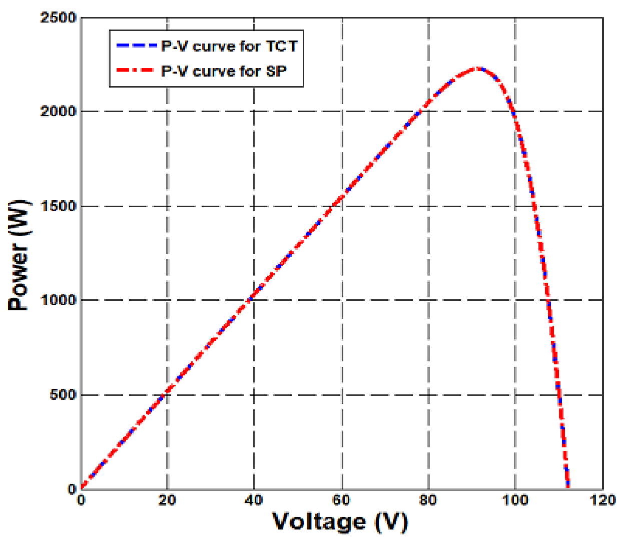


Fig. 3. *P-V* characteristics for Case 1.

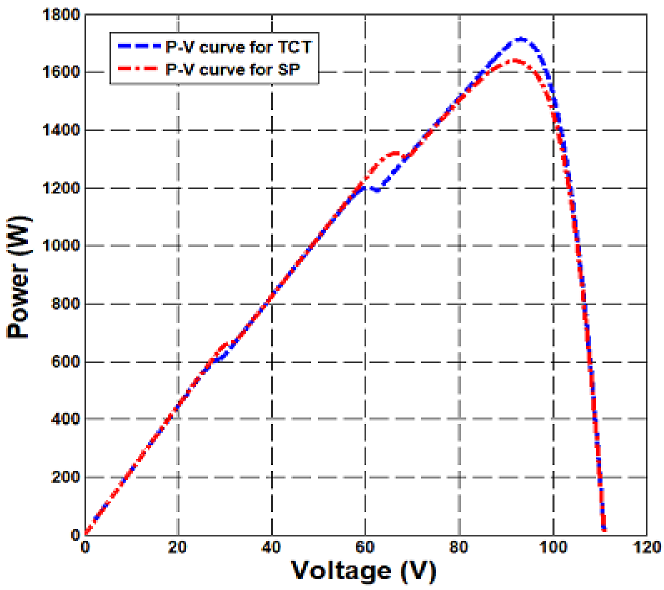


Fig. 4. *P-V* characteristics for Case 2.

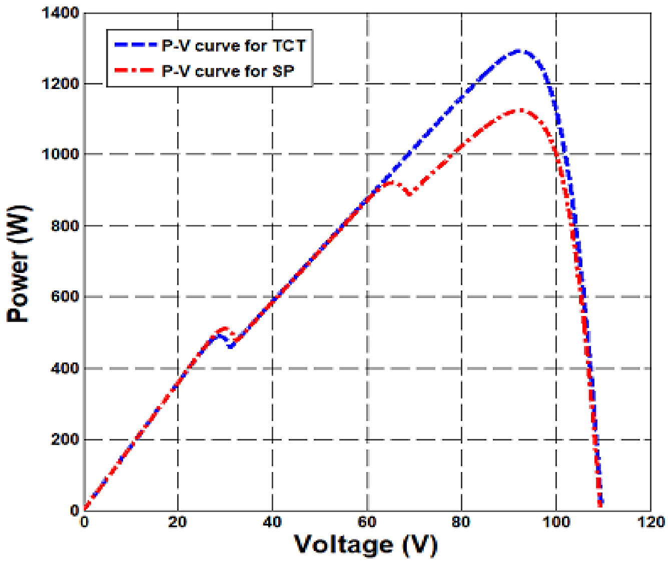


Fig. 5. *P-V* characteristics for Case 3.

Fig. 6 elucidate P-V characteristics under diagonal shading, i.e., under shading scenario represented by Case 4. In this case, the difference between the global peak power between the SP array and the TCT array increases to a much greater value (17.24 %) compared to the previous cases. Fig.7 represents the P-V characteristic for

Case 5, which is a horizontal shading scenario, and the results are of both the arrays are quite similar, and no difference could be found in the global peak points produced by SP and TCT arrays. Fig.8 represents P-V characteristics under Case 6, in which the upper two rows are under shading, making the column partially shaded. In this case, the TCT configuration produces relatively greater power output than that produced by SP array as well, but the absolute value of peak power is observed to be least in this case compared to other cases for both the configurations.

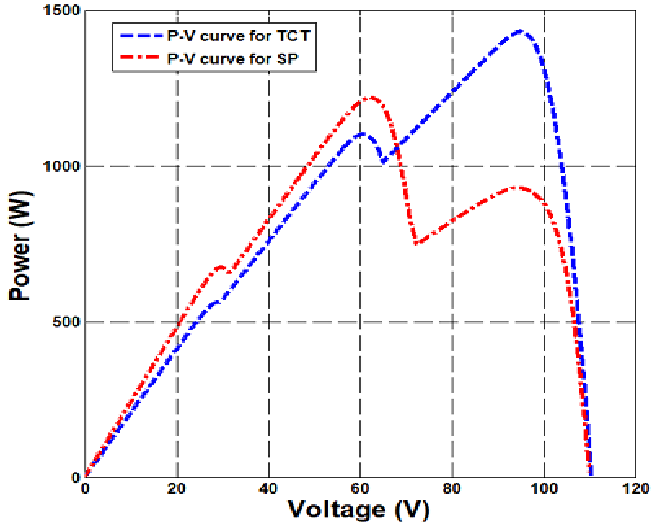


Fig. 6. *P-V* characteristics for Case 4.

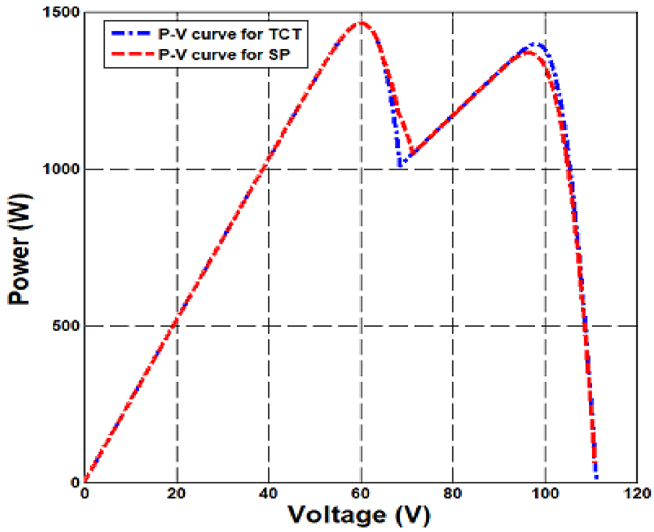


Fig. 7. *P-V* characteristics for Case 5.

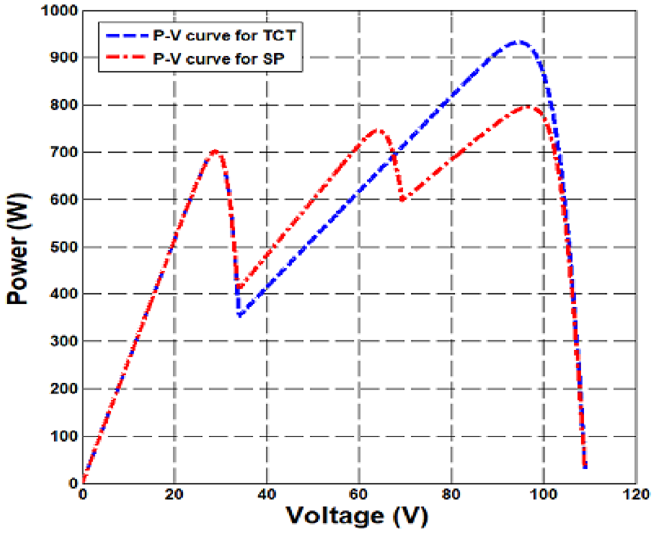


Fig. 8. *P-V* characteristics for Case 6.

The absolute values of the output parameters of SP and TCT array configuration are presented in Tables 2 and 3, respectively. It may be observed that in 2 out of 6 cases (i.e., in Cases 1 and 5), the peak power is equal for both SP and TCT arrays, while in the rest of the four cases, the power output was more in the case of TCT (also refer Fig. 9). Case 1 represents uniform irradiance over all the modules of the array and hence the similar output result; however, for Case 5, which is a horizontal shading condition, is also indifferentiable, which implies that there is no advantage of increasing the interconnection redundancy if all the modules in the same row go under shading., and TCT array will be advantageous over SP array configuration under all other shading scenarios.

Table 2. Performance parameters of SP for all the cases of shading scenarios

Cases	P_{MAX} (W)	V_{MPP} (V)	I_{MPP} (A)
Case 1	2225.4	91.78	24.24
Case 2	1637.4	92.05	17.78
Case 3	1122.6	92.78	12.09
Case 4	1219.0	61.51	19.81
Case 5	1463.3	60.34	24.25
Case 6	795.22	97.15	08.18

Table 3. Performance parameters of TCT for all the cases of shading scenarios.

Cases	P_{PEAK} (W)	V_{MPP} (V)	I_{MPP} (A)
Case 1	2225.4	91.76	24.24
Case 2	1712.2	93.22	18.36
Case 3	1290.8	92.62	13.93
Case 4	1429.2	95.63	22.67
Case 5	1463.3	60.36	24.24
Case 6	932.36	94.46	09.87

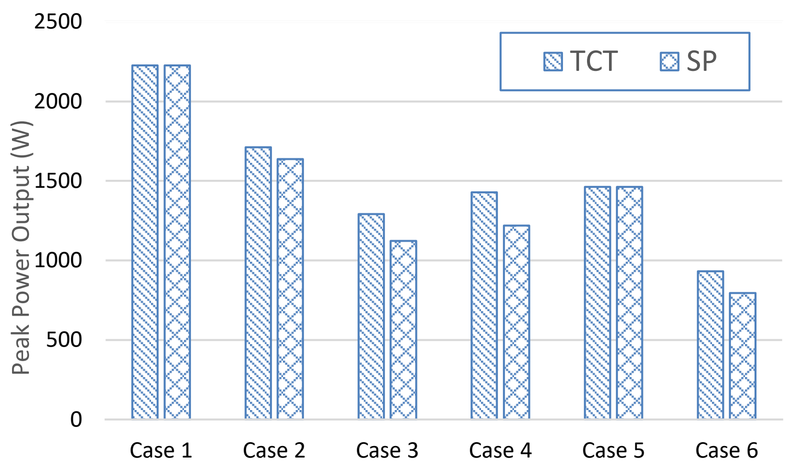


Fig. 9. Comparison of peak power outputs, under different shading scenarios.

4 Conclusions

In this paper, a comparative performance analysis of 3×3 matrix of conventional series-parallel and total cross-tied configurations is carried out under six different irradiance patterns. The produced current, voltage, and power at the global maximum power point have been reviewed to have a deeper insight into the behavior of both the PV array configurations. From the analysis, it is found that both the configurations perform equally under uniform shading and horizontal shading. Horizontal shading may be caused by adjacent rows of panels when the sun is at low altitudes, viz. during sunrise and sunsets, if the distance between each row is inadequate. TCT configuration performed better in all other shading scenarios studied in the present work. Hence there is no advantage in increasing the interconnection redundancy if the arrays are expected to perform under uniform irradiance or self-shading under low altitudes of sun. From the present work, it is also evident that if there are possibilities of the creation of other shading patterns, such as nearby buildings, poles, trees, and non-uniform dust accumulation, the performance ratio of a PV plant may be increased by increasing the interconnection redundancy.

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