Experimental Study On SP And TCT Connections Of PV Modules Under Realistic Shading Conditions

Rupendra Kumar Pachauri, Antima Tanwar, Sparsh R. Tripathi, Deepak Kumar

Abstract: The aim of this paper is to calculate the impact on the performance of photovoltaic (PV) systems of the realistic causes of the shading effect. Four 20W solar PV modules (2x2 size) are considered and arranged in series-parallel (SP) and total-cross-tied (SP) for extensive analysis. In addition, the performance effects of current-voltage (I-V) and power-voltage (P-V) curves to conduct the comprehensive analysis will be taken into account with two types of shading patterns such as fallen leaf and bird dropping conditions on the solar PV modules. Finding multiple power maxima points such as local and global maximum power points (GMPPs) because of the shadow effect is also reduced by the output PV array power. In separate shadow cases, the performance parameters such as power on GMPP, minimal power loss and fill factor (FF) will be analyzed experimentally for both the PV array configurations.

Index Terms: partial shading effect, photovoltaic system, power losses, bird dropping, leaf fallen conditions, photovoltaic system, solar energy

1 INTRODUCTION

The global energy crisis has motivated renewable energy sources (RES) such as PV, wind power, biofuels and geothermal energy etc. Sustainable energy resources have been explored by scientists due to fossil-fuel depletion and environmental damage issues [1]. In addition to the potential and respect for the environment of RES, their economiccompetitiveness is constantly increasing. Solar radiation is the main energy source in the world and therefore the direct transformation of light to energy is one of the best technology in the world. The efficiency, reduced costs and low maintenance of the Solar PV modules have increased and their use is thus increasing year after year. With partial shading conditions (PSCs), the efficiency of the PV module is reduced. Several factors like the passing clouds, commercial high rise building, trees and birds cause PV system shade. PV modules receive different solar irradiation values under PSCs. As such, the PV array's P-V and I-V characteristics have multiple peaks, resulting in system power losses. The PV array reconfiguration method is the PV array configuration system for reducing the power losses [2].

1.1 Literature review

Several scientists now explore the solution for improving PV system performance during PSCs using satisfactory methods, such as bypass diode integration with the modules and altering the position of the PV module with the fixed electrical connections. In this scenario, the latest available literature from the spam year 2013-2018 reports one of the most appropriate method for reconfiguration of PV modules to PV array systems.

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The PV modules are generally arranged electrically in series and parallel to the load power requirement. When one or more panels are shaded, the power generated by the PV array decreases significantly. In [3], the authors rearranged in a PV array the conventional TCT connections of integrated modules based on Su-Do-Ku puzzle. In addition, a comprehensive study is conducted to compare the results obtained such as power losses, FF and GMPP position of both configurations in four shading cases such as short narrow (SN), short wide (SW), narrow wide (NW) and long wide (LW). In an experimental study, The MATLAB / Simulink model identifies and validates local and global maximum power points (GMPPs) under shading conditions [4]. Three solar panel connected series are considered to determine the impact of non-uniform irradiation on GMPP location [5]. In order to achieve the MPP during the shaded series-parallel (SP), TCT and bridge-link (BL) modules, an experimental and MATLABSimulink study is conducted, it found that the TCT has better results than others [6, 7]. The authors of [8, 9] designed the 3x3 size of the PV array in series connections to show the shadow impact on the P-V curve and the GMPP is 40W. In [10], series and parallel PV array connections are investigated under three shading conditions. Results for improved FF, low mismatch losses (MML) and a minimum number of GMPPs for parallel connections are observed. For the validation of 230W PV panels (eight numbers) arranged in series connections, simulated and experimental results are compared and performed under three shading test schemes. The placement of bypass diode with the PV cell strings is analyzed during the study, decreasing to the shadow effect [11]. Optimization technique is used to spread the shadow of the TCT panel connections and compares the results in terms of power increase, improved FF and minimum power losses in PSCs with the Su-Do Ku puzzle-based connections [12]. In [13], Many PV array configurations such as series, parallel, SP, TCT, BL, HC and proposed new PV array configuration of 6x6 size are considered for extensive study under PSCs. The proposed ' new ' configuration is observed to react better than others. An improved Su-Do-Ku pattern is obtained from Su-Do-Ku electrical connections given in [14] to investigate performance in four shadow test cases such as SW, LW, SN and LN. In addition, Su-Do-Ku improved with minimum power losses in all test cases [14]. In [15], the authors considered passing clouds a shadow effect on the PV array for SP, HC, BL, TCT and Su-Do-Ku configurations. Under the distinctive shadow patterns, the performance of conventional TCT and Su-Do-Ku puzzle-based reconfigured TCT (RTCT) configuration is compared [16]. Results from TCT, hybrid SP-TCT and Su-Do-Ku configurations are analyzed and found that PV array Su-Do-Ku connections have better results in terms of high FF, low power losses and fewer MPPs (P-V curve smoothness) [17]. The performance parameters of existing PV panel connections as SP and TCT are compared with progressive shading cases in an experimental study inUnder SW, LW, SN and LN shading conditions, the output power of a PV array improves by using various configurations such as electrical array configuration (EAR), Futoshiki, and module-fixed electrical connection (PRM-FEC) physical relocation [19, 20]. Using Magic Square (MS) puzzle is modified in [21] conventional TCT configuration and performance assessment is performed under SW, LW, SN and LN shading conditions. In all shading conditions, the MS configuration has the best results. Experimentally, significant high value of new configuration results is obtained and compared to basic configurations [22]. Optimal PV panel connections in an array are chosen and compared to conventional SP and TCT panel interconnections under the predefined shading effects and found optimal connections to best results [23]. In [24], the performance analysis of SP, BL and TCT configurations is compared to an electrical PV array based shadow dispersion scheme (SDS) under LN and SW shadow conditions. In addition, SDS has the best results in all configurations. An experimental study on the performance of a PV system is conducted in [25] to assess shadow impacts and validated with MATLAB/Simulink modelling to confirm the reliability of the model offered.

2 EXPERIMENTAL SYSTEM

The developed experimental setup is comprised mainly two sections such as solar PV array (2x2 PV modules) and performance measurement system. In the section (i), Solar PV array comprised with 2×2 PV modules are integrated in SP and TCT connections. In the second (ii), two multi-meter systems are integrated with the rheostat resistive load (360 ohm) to measure the real time voltage and current. Performance evaluation of developed system is done to show the impact on voltage and current by the observation of P-V and I-V curves. The specifications of 20W Poly-Si solar PV Module (Mfd.: Spark Solar, Model: SS2018P) is used as a primary components to comprise the experimental set up are listed in Table-1. The experimental setup developed is shown in Fig. 1 as,

TABLE 1
SPECIFICATIONS OF 20W POLY-SI SOLAR PV MODULE

Parameters	Specifications
Max. power (Pmax)	20W
Max. Voltage (Vm)	18.25W
Max. Current (Im)	1.10 A
Open-circuit voltage (Voc)	21.96V
Short-circuit current (Isc)	1.17A

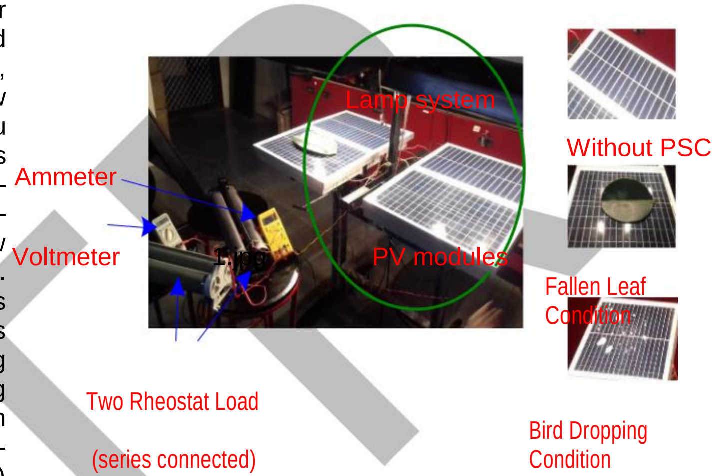


***Fig. 1**. Experimental setup of solar PV performance assessment under distinguish shading conditions*

3 PHOTOVOLTAIC SYSTEM

The electrical-equivalent circuit demonstrated in Fig. 2 Solar cell is capable of transforming sunlight into dc current and PV voltage as,

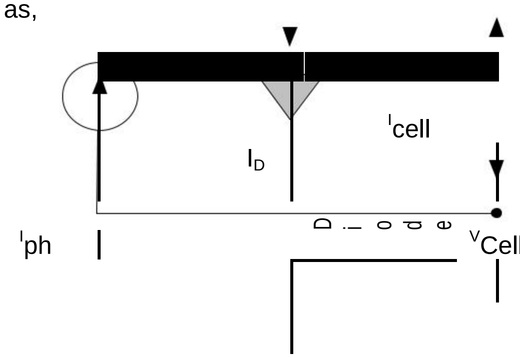


***Fig. 2** Equivalent circuit of solar cell*

The current generated from solar cell (I_{cell}) can be demonstrated in equations as,

$$I_{cell} = I_{ph} - I_D \quad (1)$$

$$I_{cell} = I_{ph} - I_o \left[\exp\left(\frac{qV_C}{AkT_C} \right) - 1 \right] \quad (2)$$

Where, I_{ph} : photocurrent of solar cell (A), I_D : diode current (A), I_o : diode reverse saturation current (A), q : electron charge (Coulomb), V_C : cell voltage (V), A : ideality factor, k : Boltzmann's constant (J/K), T_C : cell temperature (^oC).

The electrical connections of utilized 20W PV modules to form follows in Fig. 3,
the SP and TCT connections of 2x2 size PV array are given as

Iarray Iarray

I I I1 I_2

1 2

Varray Varray

(a) SP (b) TCT

Fig. 3 PV array configuration

4 RESULTS AND DISCUSSION

There is a thorough study to show the impact of shadowing patterns- 1 and 2 (each shading patterns has three cases: a, b, and c) on PV array configurations such as SP and TCT. For the characterization of 2×2 size solar PV system, the maximum irradiation level is kept as 270W/m^2 (for non-shading condition). The results of this study are as follows,

Performance analysis of PV system (2x2 size) under uniform irradiation

Performance analysis of PV system under leaf fallen shading pattern (cases: a, b and c)

Performance analysis of PV system under bird dropping shading pattern (cases: a, b and c)

4.1 Performance analysis of PV system (2x2 size) under uniform irradiation

P-V and I-V characteristics of 2×2 size PV system under uniform irradiation condition is found as I_{SC} and V_{OC} are given as 0.540A and 36.6V respectively. Moreover, maximum power is generated as 13.70W. The electrical performance curves are shown in Fig. 4 as,

0.6 14

0.5 12

4.2 Performance analysis of PV system under leaf fallen shading pattern

4.2.1 I-V and P-V curves under the Case-a of single leaf fallen shading pattern

The non-linear behavior of I-V and P-V curves are obtained due to shading case-a of leaf fallen shadow pattern. The performance behavior of SP and TCT configuration is compared. The electrical parameters such as VOC and ISC are observed as 38.5V and 0.570A for SP configuration respectively. Moreover, the electrical parameters such as VOC and ISC are observed as 37V and 0.56A for TCT configuration respectively. Maximum current (Im) is found 0.255A and 0.334A for SP and TCT respectively. Furthermore, maximum voltage (Vm) is calculated as 35.3V and 33.1V respectively for SP and TCT configurations. Under this investigation, the power loss is found minimum, higher power at GMPP and improved FF as 2.64W, 11.06W and 0.533 in TCT configuration, which is compared with SP configuration. I-V and P-V curves are shown in Fig. 5.

0.7 SP

0.6 TCT

(A) 0.5

0.4

0.3

0.2

0.1

0

0 10 20 30 40

Voltage (V)

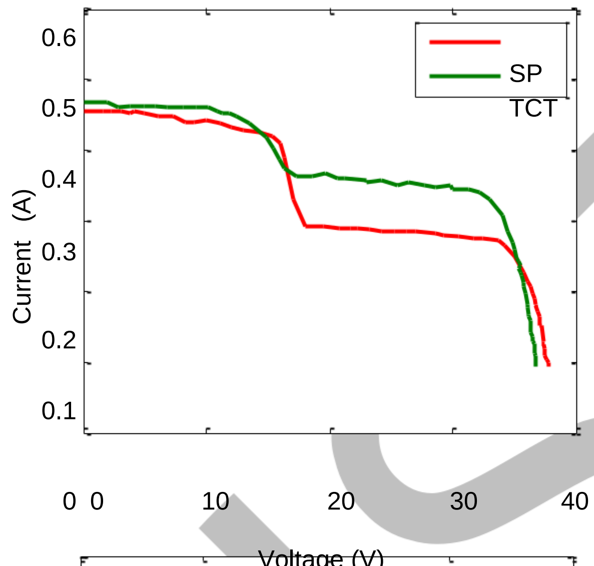
(a)

12

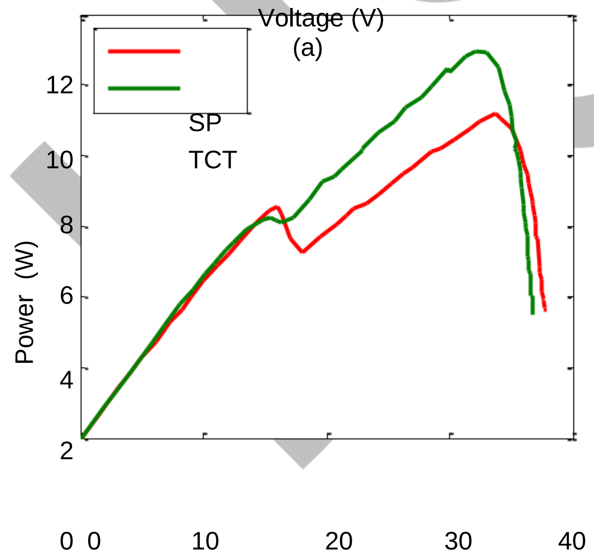
SP

4.2.2 I-V and P-V curves under the Case-b of two leaf fallen shading pattern

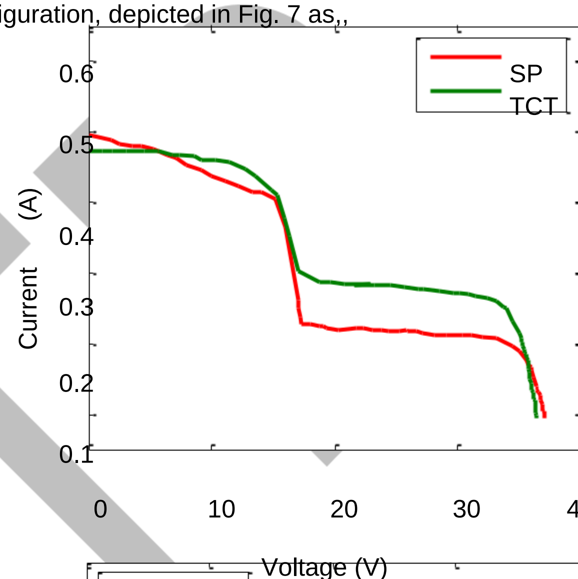
Due to shading case-b of leaf-fallen shadow pattern, the non-linear behavior of I-V and P-V curves is obtained. The SP and TCT configuration performance behavior is compared. For SP configuration, the electrical parameters such as VOC and ISC are respectively observed as 38V and 0.456A. In addition, electrical parameters such as VOC and ISC for TCT configuration are observed as 37V and 0.466A respectively. Maximum current (Im) for SP and TCT respectively is 0.2720A and 0.341A. In addition, for SP and TCT configurations, the maximum voltage (Vm) is calculated as 33.8V and 32.2V respectively. Under this investigation, in TCT configuration, the power loss is found to be minimal, higher power at GMPP, and improved FF as 2.72W, 10.98W, and 0.636 compared to SP configuration. I-V and P-V curves are depicted in Fig. 6.



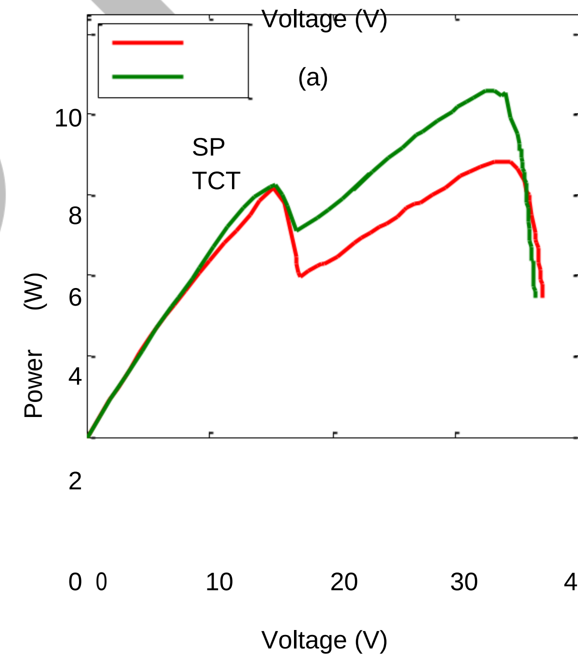
(a)



behavior of SP and TCT is compared. For SP configuration, electrical parameters such as VOC and ISC are respectively 37V and 0.495A. Electrical parameters like VOC and ISC for TCT configuration are 36.5V and 0.474A respectively. The value of Im for SP and TCT configuration is 0.0.198A and 0.260A. The value of Vm is 34.5V and 33.1V for SP and TCT configurations. Under this investigation, the power loss at GMPP is found to be minimal, higher power at GMPP and improved FF as 5.094W, 8.606W and 0.497 compared to SP configuration, depicted in Fig. 7 as,,



(a)



(b)

Fig. 7*(a) I-V (b) P-V curves of solar PV system under the Case-C of single leaf fallen shading pattern*

4.3 Performance analysis of PV system under bird dropping shading pattern

Voltage (V)

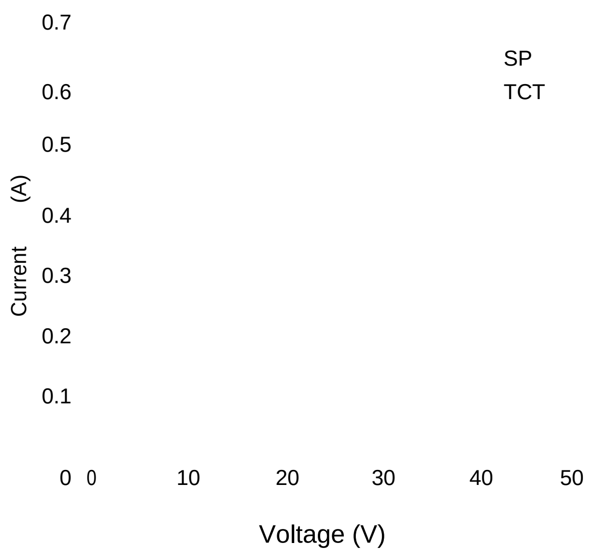
(b)

Fig. 6 (a) I-V (b) P-V curves of solar PV system under the Case-b of single leaf fallen shading pattern

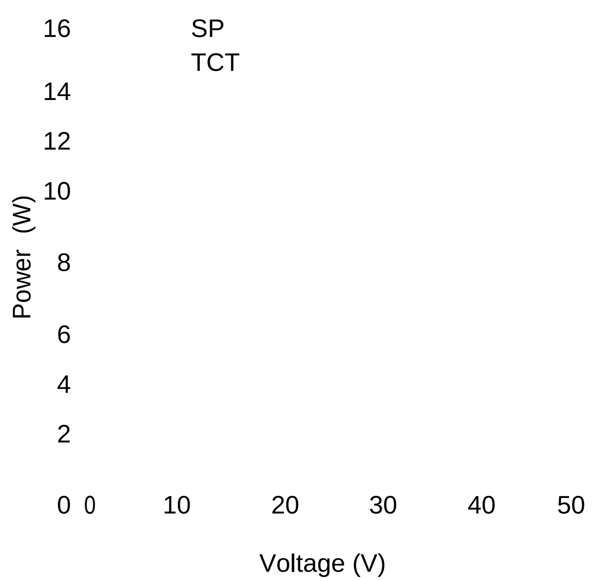
4.2.3 I-V and P-V curves under the Case-c of three leaf fallen shading pattern

Curves I-V and P-V's non-linear behavior is obtained due to shading case-c of leaf-fallen shadow pattern. Performance

maximum value of Im as 0.348A and 0.367A, respectively. For SP and TCT configurations, the value of Vm are obtained as 33.1V and 38.4V. This study found that the power loss of GMPP as 0.10W, 13.60W and 0.538 compared to SP configuration was minimal, higher value of power and improved FF as shown in Fig. 8.



(a)



4.3.1 I-V and P-V curves under the Case-a of bird dropping shading pattern

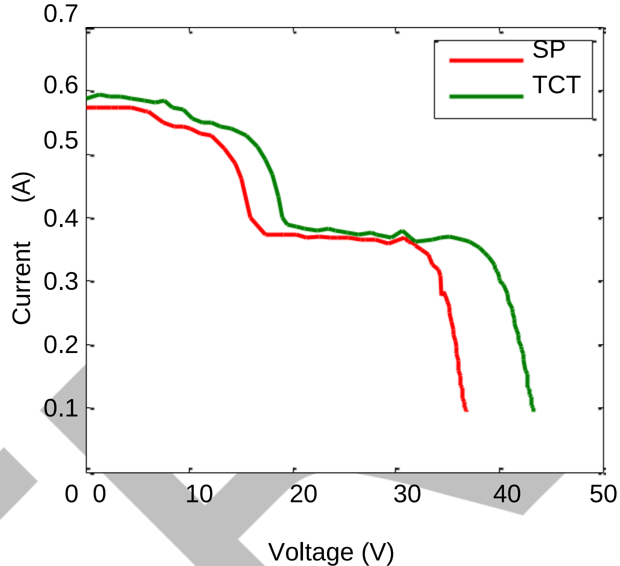
Non-linear behavior of I-V and P-V curves is achieved by shading a case with bird dropping shadow. SP and TCT are comparable in their performance behavior. Electric parameters such as ISC and VOC are 39.5V and 0.58A for SP configuration. TCT configuration has 42.2V and 0.594A electric parameters like VOC and ISC. The SP and TCT based electrical connections have

(b)

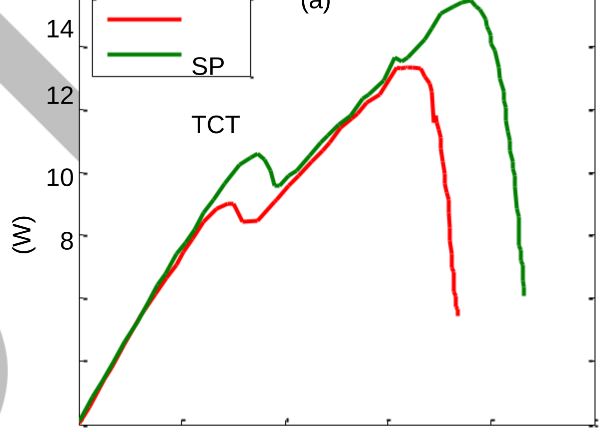
Fig. 8(a) I-V (b) P-V curves of solar PV system under the Case-a of single PV module bird dropping shading pattern

4.3.2 I-V and P-V curves under the Case-b of bird dropping shading pattern

Due to shade case-b of a bird dropping shadow pattern, I-V and P-V are nonlinear in nature. The SP and TCT configuration performance behavior is comparable. Electrical settings for SP configuration, like VOC and ISC, are 39V and 0.572A respectively. For electrical parameters such as ISC and VOC, 32.5V and 0.349A for the TCT configuration are also observed. For SP and TCT, 0.349A and 0.354A are found as maximum value of Im. The values of Vm for SP and TCT configurations are calculated as 32.5V and 38V. Under this investigation, the power loss at GMPP is found to be minimal, maximum global power and improved FF as 0.25W, 13.45W and 0.542 for TCT configuration, which is compared to SP configuration. The non-linear behavior of I-V and P-V curves are shown in Fig. 9 as,



(a)

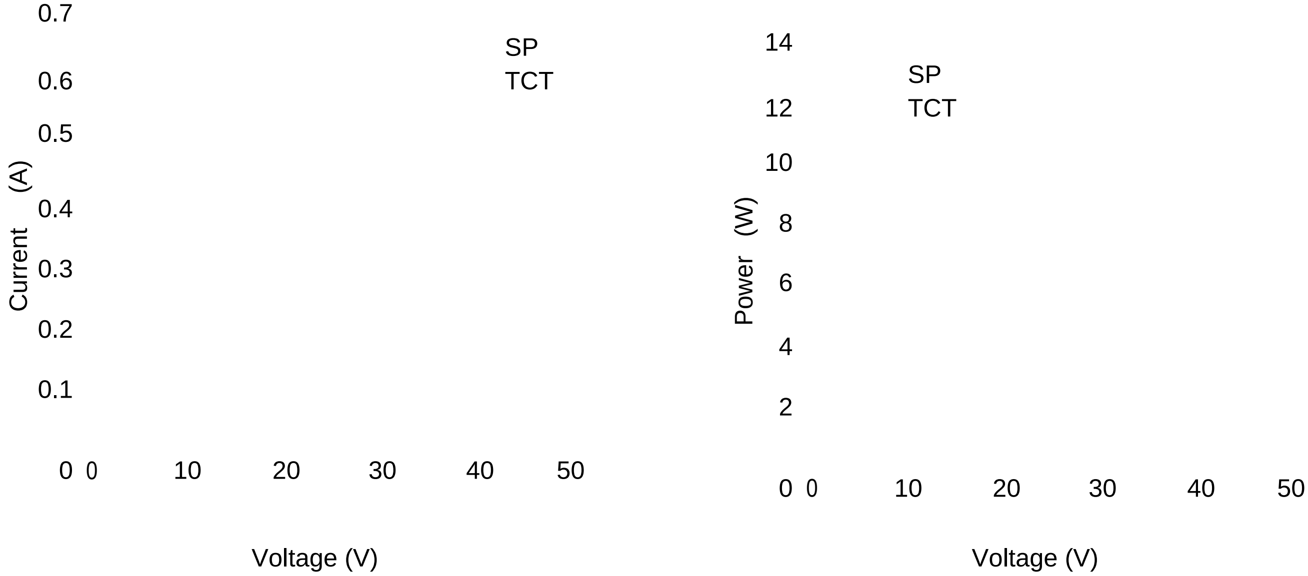


(b)

Fig. 9*(a) I-V (b) P-V curves of solar PV system under the Case-b of single PV module bird dropping shading pattern*

4.3.3 I-V and P-V curves under the Case-c of bird dropping shading pattern

The shading case-c of the bird dropping shadow pattern acquires non-linear I-V and P-V curves. Comparison of the performance parameters of the respective SP and TCT configurations. Electrical parameters such as VOC and ISC are respectively observed as 38.5V and 0.568A for SP configuration. Moreover, electrical performance parameters such as VOC and ISC are observed as 42.5V and 0.555A, respectively for TCT configuration. The value of Im is found to be 0.348A and 0.339A for SP and TCT. The value of Vm is also calculated for SP and TCT configurations as 32.1V and 39.1V respectively. Under this investigation, the minimal power loss, maximum power at GMPP and improved FF are found as 0.41W, 13.29W and 0.563 for TCT configuration and compared to SP configuration. The effect of shading on the PV system is reflected from the obtained nature of I-V and P-V curves, shown in Fig. 10 as,



(a) (b)

Fig. 10*(a) I-V (b) P-V curves of solar PV system under the Case-c of single PV module bird dropping shading pattern*

A statistical based extensive comparison between all the important performance parameters like GMPP power and voltage, power loss and FF of both the considered configurations (SP and TCT) under the two types of shadowing patterns are carried out and graphically represented in Fig. 11(a)-(d). Moreover, the quantitative analysis of entire performance parameters of PV system under the investigation is depicted in Table-2 as,

TABLE 2

QUANTITATIVE ANALYSIS OF OBTAINED PERFORMANCE PARAMETERS

Performance parameters	Shading Pattern-I: Fallen Leaf Condition						Shading Pattern-II: Bird Dropping Condition					
	Case-a		Case-b		Case-c		Case-a		Case-b		Case-c	
	SP	TCT	SP	TCT	SP	TCT	SP	TCT	SP	TCT	SP	TCT
O. C. voltage (VOC) (V)	38.5	37	38	37	37	36.5	39.5	42.2	39.0	42.2	38.5	42.5
S. C. current (ISC) (A)	0.570	0.56	0.456	0.466	0.495	0.474	0.58	0.594	0.572	0.587	0.568	0.555
Maximum voltage (Vm)	35.3	33.1	33.8	32.2	34.5	33.1	33.1	38.4	32.5	38	32.1	39.1
Maximum current (Im)	0.255	0.334	0.272	0.341	0.198	0.260	0.348	0.367	0.349	0.354	0.348	0.339
Power at GMPP (W)	9.002	11.06	9.194	10.98	6.831	8.606	11.52	13.60	11.36	13.45	11.2	13.29
Voltage at GMPP (V)	35.3	33.1	33.8	32.2	34.5	33.1	33.1	38.4	32.5	38	32.1	39.1
Power loss (W)	4.698	2.64	4.506	2.72	6.869	5.094	2.18	0.10	2.34	0.25	2.5	0.41
Fill factor	0.410	0.533	0.530	0.636	0.372	0.497	0.502	0.538	0.509	0.542	0.512	0.563

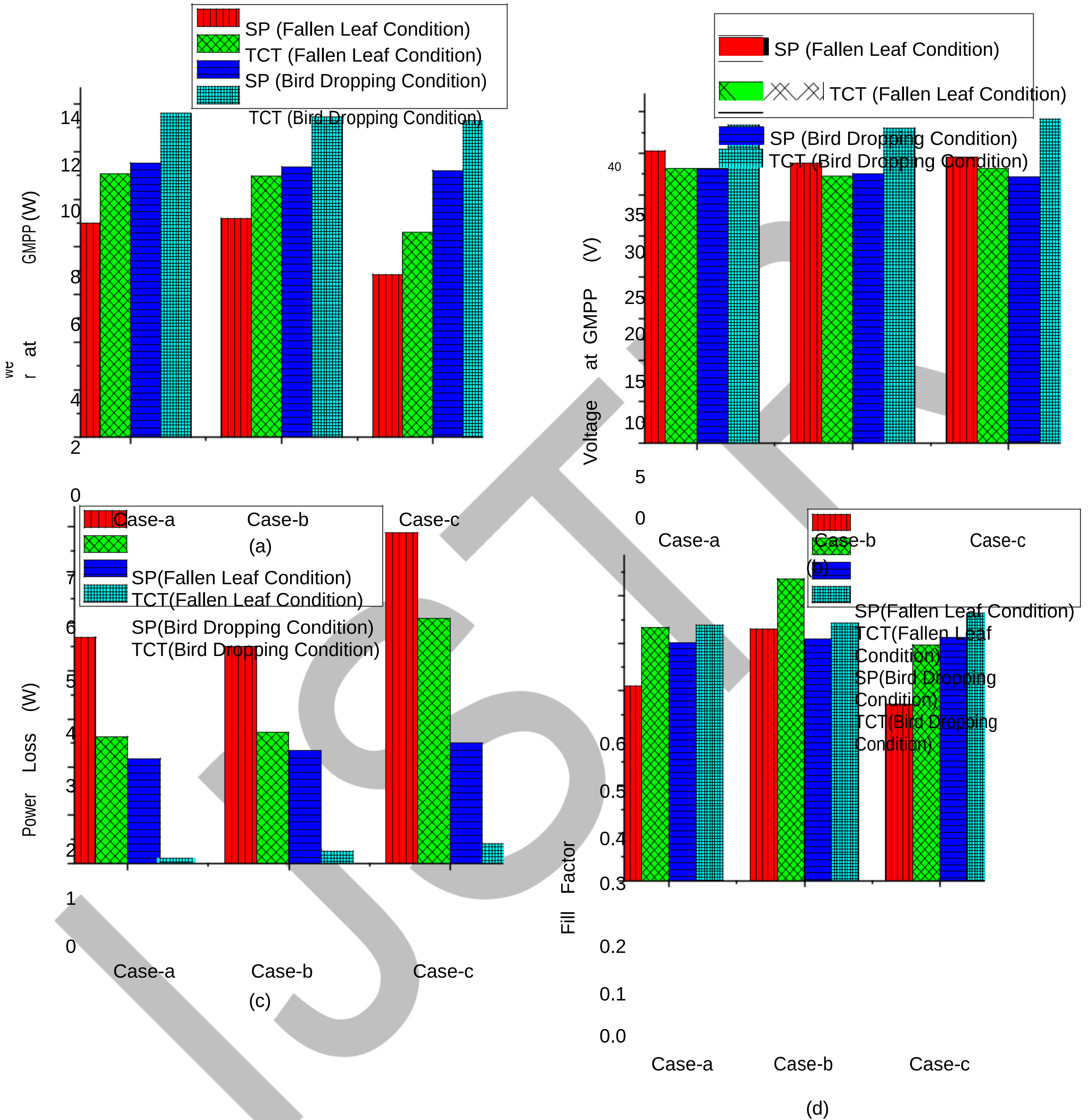


Fig. 11 Statistical analysis of performance parameters (a) Global power (b) Voltage at GMPP (c) Power loss (d) FF

5 CONCLUSION

An Experimental analysis of TCT configuration with the SP configuration of PV array for performance improvement is carried under two types of realistic shadow patterns such as leaf fallen and bird dropping conditions. Losses in power, mismatch loss, power enhancement and FF have been compared for the both configurations. Approximate GMPP location and partially shaded array nominal voltage are validated. Thus, the proposed configuration is helpful in the design of PV arrays, and is especially useful for large scale PV farms. The TCT configuration has better results, which reduces the maximum power point tracking efforts. The important quantitative points of study under the experimental investigation are given as, In the shading case-1 (fallen leaf shadow pattern), power at GMPP, minimal power loss and improved FF are observedas 11.06W, 2.64W and 0.533 respectively. In the shading case-1 (bird dropping shadow pattern), power at GMPP, minimal power loss and improved FF areobserved as 13.60W, 0.10W and 0.538 respectively. Moreover, it is observed TCT has best results in all the aspect of performance parameters under all the considered shading cases of both realistic shadow patterns.

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