Experimental study on electrical connections of PV system for improved performance under shadow test cases

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Abstract

In this paper, an experimental study is carried out in order to compute the impacts of shading effect on photovoltaic (PV) system performance. Four numbers of 20W solar PV modules are considered and arrange in the 2x2 size of array for extensive analysis. Moreover, a performance comparison is carried out for all the four PV modules organized in series-parallel (SP), Total cross-tied (TCT) and Latin Square puzzle based Latin Square-Total cross-tied (LS-TCT) electrical connections. In addition of this, three types of shadow test cases are taken to show the impact on behaviour of current-voltage (I-V) and power-voltage (P-V) curves. Furthermore, the output power from PV array reduces as well as P-V curves exhibit multiple power maxima points such as local and global maximum power point (GMPP) due to shadow effect. The performance index parameters such as power at GMPP, minimum power losses, fill factor (FF) and efficiency are analysed experimentally under the distinguish shadow cases.

1. Introduction

Today, PV system technology is gaining more attention and is being considered as a primary source of renewable energy in rural and metro cities [1]. PV system for power generation deals with many challenges such as its low conversion efficiency from light into the electricity and impact of environmental factors can be understood by the behaviour of PV system short circuit current (I_{SC}). The technical limitations of PV cells / modules can be removed as much as possible through the manufacturing process, but environmental causes can't be avoided. Non-uniform irradiation level/partial shading conditions (PSCs) on the PV array is a major cause among environmental causes, which has a noticeable impact on the uneven behaviour of the PV module in particular [2]. The impactful causes of the PSCs on the PV array is due to dust accumulation of the PV module surface and shadows on the array due to passing clouds, nearby trees, high-rise buildings, bird-falling etc.

Several researchers are now exploring the solution to enhance the performance of the PV system during the PSCs by satisfactory methods such as bypassing the integration of diodes into the modules and altering the position of the PV module with fixed electrical connections in the array. One of the most appropriate methods available in the current scenario is the reconfiguration of PV modules in PV array arrangements reported in the recent available literature for the spam year 2013-2020.

Generally, the PV modules are electrically arranged in series and parallel to fulfil the load power requirement. The power generated from the PV array decreases considerably if one or more panels are shaded. In [2], the authors rearranged the conventional total cross-tied (TCT) connections of modules integrated based on Su-Do-Ku puzzle in a PV array. Moreover, an extensive investigation is done to compare the obtained results such as power losses, FF and GMPP position

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of both configurations under the four types of shading cases such as short narrow (SN), short wide (SW), narrow wide (NW) and long wide (LW) . Local and GMPPs are identified in an experimental study and validated with the MATLAB/Simulink model under shading conditions [3]. Series connected three panels are considered to elaborate the impact of non-uniform irradiation on GMPP location [4]. An experimental and MATLAB/Simulink study is carried out to achieve the MPP during the shaded series-parallel (SP), TCT and bridge-link (BL) arranged PV modules, it identified that the TCT has best results as compare to other ones [5, 6]. The authors of [7, 8] designed the 3×3 size of PV array in series connections to show the impact of shadow on P-V curve and the GMPP is found 40W. In [9], an investigation is done on the series and parallel connections of PV array under three shading conditions. The results are observed in terms of improved FF, low mismatch losses (MML) and minimum number of GMPPs are found for parallel connections. Simulated and experimental results are compared for validation of 230W PV panels (eight numbers) arranged in series connections and performed under three shading test schemes. Diminishing to shadow effect, placing of bypass diode with the PV cell strings is analysed during the study [10]. Optimization technique is used to scatter the shadow on TCT connections of panel and compared the results with Su-Do-Ku puzzle based connections in terms of power enhancement, improved FF and minimum power losses under PSCs [11]. In [12], numerous PV array configurations such as series, parallel, SP, TCT, bridge-link (BL), honey-comb (HC) and proposed new configuration of 6×6 size PV array are considered for extensive study under PSCs. Proposed 'new' configuration has better response as compared to others. An improved Su-Do-Ku pattern is achieved from electrical connections of Su-Do-Ku given in [12] to investigate the performance under four shadowing test cases such as short wide (SW), long wide (LW), short narrow (SN) and long narrow (LN). Moreover, in all the test cases improved Su-Do-Ku has best results as minimum power losses [13]. In [14], authors have considered passing clouds as shadow effect on PV array for investigation on SP, HC, BL, TCT and Su-Do-Ku configurations. Performance of conventional TCT and Su-Do-Ku puzzle based reconfigured TCT (RTCT) configuration are compared under the distinguish shadow patterns [15]. The results obtained from TCT, hybrid SP-TCT and Su-Do-Ku configurations are analysed and found that Su-Do-Ku connections of PV array have better results in terms of high FF, low power losses and less number of MPPs (smoothness of P-V curves) [16]. To compare the performance parameters of existing connections of PV panels as SP and TCT in an array under progressive shading cases, an experimental study is carried out in [17]. The output power of a PV array improves under SW, LW, SN and LN shading conditions by using different configurations such as electrical array configuration (EAR), Futoshiki, and the physical relocation of module- fixed electrical connection (PRM-FEC) [18, 19]. In [20] conventional TCT configuration is modified using Magic Square (MS) puzzle and performance assessment is done within the SW, LW, SN and LN shading conditions. MS configuration has best results in

all shading conditions. Significant high value of results of novel configuration are obtained experimentally and compared with basic configurations [21]. Optimal connections of PV panel in an array are opted and compared with the conventional SP and TCT interconnections of panels under the predefined shading effects and found that optimal connections have best results [22]. In [23], performance analysis of SP, BL and TCT configurations are compared with a shadow dispersion scheme (SDS) based electrical connections of PV array under a LN and SW shadow conditions. Moreover, SDS has best results among the all configurations. In [24], an experimental study is done on the performance of a PV system in order to evaluate the impacts of shadow and validated with MATLAB/Simulink modelling for confirmation the reliability of the offered model. A comprehensive analysis with a 4×4 size novel Latin-based puzzle-based TCT configuration (LS-TCT) to reduce the shading impacts. In addition, in the proposed configuration, the fill factor for the shadowing case is 9.91, compared to 8.59 for traditional TCT configuration. In general, LS-TCT configuration efficiency is higher than in TCT configuration [25]. In [26], the authors have focused on the various techniques that could negate the impact of partial shading and enhance the output under such conditions. In order to improve the power extraction under PSCs. In [27], Authors developed an electromechanical relay-based hardware system to switch 3×3 complete cross-tied (TCT) connections from series-parallel (SP) configuration. The PV system output analysis is conducted efficiently in terms of power and voltage at global maximum power point (GMPP), power loss, and fill factor (FF). MATLAB simulation validates all hardware results obtained. A thorough analysis of faults including non-uniform shading on SP, HC and TCT PV systems is presented. A special case of multiple PV array faults under non-uniform irradiance is also investigated to examine their cumulative effect on different PV interconnections [28, 29].

1.1. Conventional PV array configurations

Researchers are extensively investigating the configurations of the PV module arrays. The following six module configurations are commonly observed in [30, 31] as,

- **Series Array**: PV modules are connected in series as shown in Figure 1(a). That enhances array voltage performance for load application.
- **Parallel Array**: As shown in Figure 1(b), PV modules are connected in parallel. This type of PV module electrical connection increases the current array performance.
- **Series-Parallel Array**: In sequential order, PV modules are connected in a string first, followed by parallel, as illustrated in Figure 1(c). These multiple strings are known as the SP circuit which increases load voltage and power output. In addition, most widely used configurations are the SP configuration.
- **Total Cross-Tied Array**: As shown in Figure 1(d), PV modules are linked serially and parallel cross-linked. This design includes a framework for

connecting the modules in parallel and in sequence. Multiple PV modules are first connected in parallel; these parallel modules are then connected in series. This connection framework can overcome sequence and parallel arrays drawbacks.

- **Bridge-Link Array**: A bridge architecture is used to connect PV modules as shown in Figure 1(e). If configurations of this kind are partially shaded, it will also affect the neighbouring modules, raising the total voltage and current output.

- **Honeycomb Array**: In a honeycomb configuration, PV modules are connected as shown in Figure 1(f). In some but not all shading conditions, these configurations can common power output losses. HC design weakness therefore lacks robustness.

(a) Series

(b) Parallel

(c) Series-Parallel
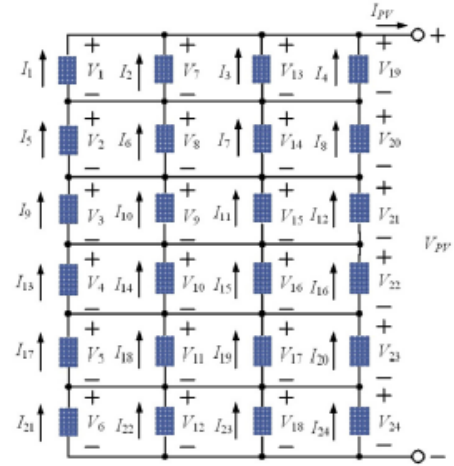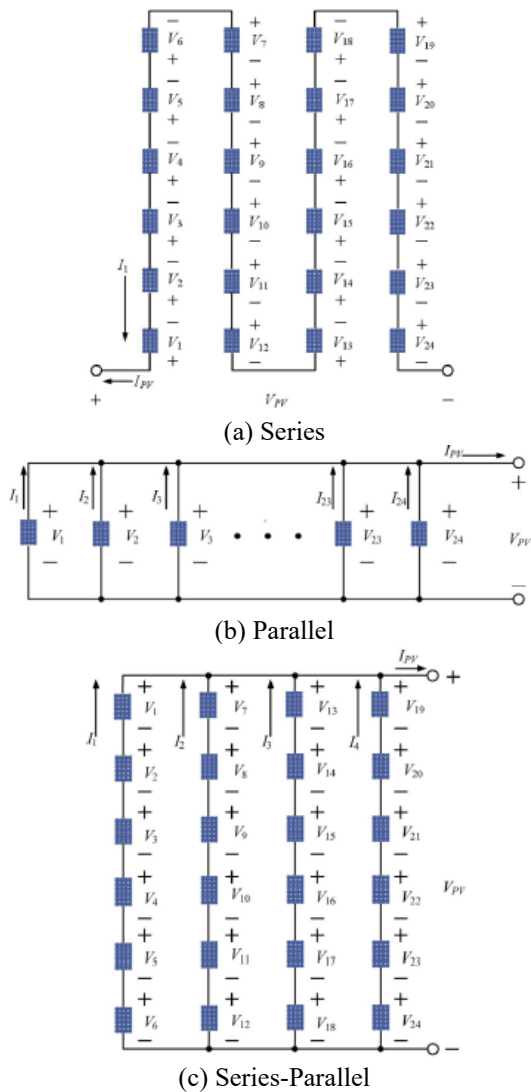
(d) Total cross-tied
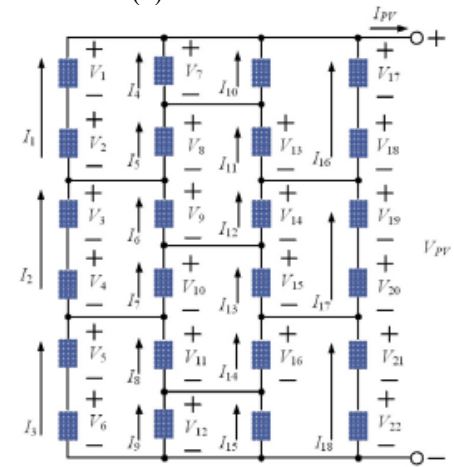
(e) Bridge-link
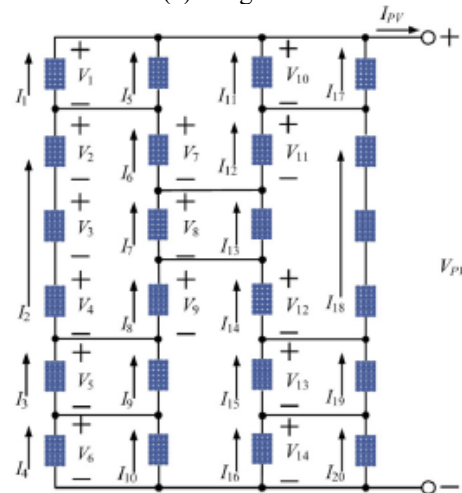
(f) Honey-comb

Figure 1. Electrical arrangement PV array configurations [30, 31]

1.2. Novelty of work

In present work, an experimental study is carried out to estimate its I–V and P–V curves to show the effect of solar irradiance variation. The salient points of the present study are as follows,

- In order to test the strength of the proposed LS-TCT configuration, experimental comparison with the classical SP, TCT configurations is also analysed under three types of shadow test cases.
- Experimental results are useful for estimating the performances of PV systems under PSCs before the installation process.

2. Experimental setup and specifications

The developed experimental setup is comprised mainly two sections as solar PV array and performance measurement system. In first section: Solar PV array comprised with 2×2
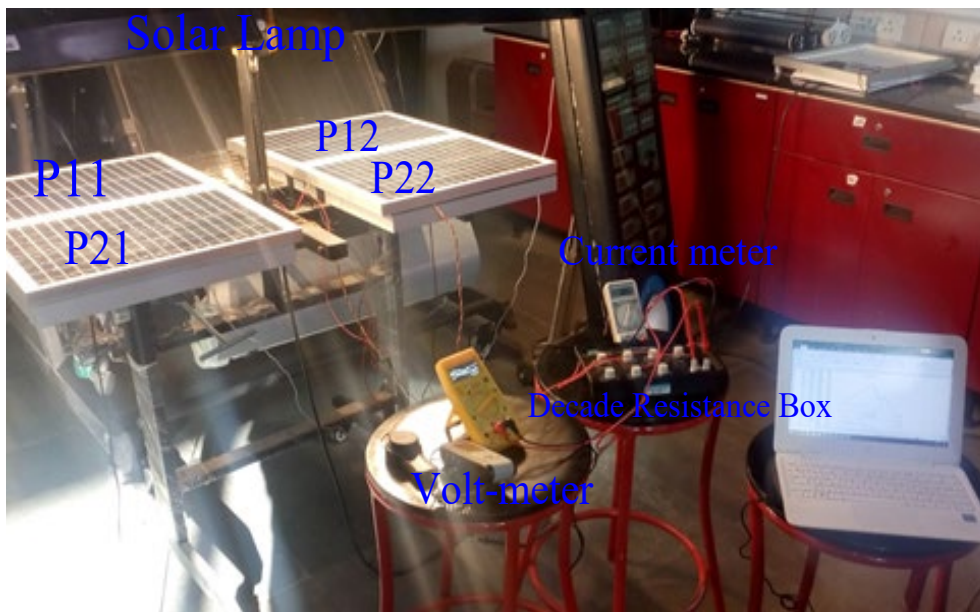
PV modules are integrated in SP, TCT and LS-TCT connections. In second section entitled performance measurement system: Two multi-meter systems are integrated with the decade resistive load to measure the real time voltage and current. Performance evaluation of developed system is done to show the impact on voltage and current by the observation of P-V and I-V curves. The specifications and utilizations of all the supportive components to comprise the experimental set up are listed in Table-1. The developed experimental setup is depicted in Figure 2 as,

Figure 2. Experimental set-up

Table 1. Specifications and role of supportive items used in developed experimental setup

Section	Components	Specifications	Role/function
		- PV array power: 20 W O. C. voltage: 22.58 V S. C. current: 1.19 A I_{mpp}: 1.08A, V_{mpp}: 18.82V - No. of PV module: 4 (2x2 array)	2x2 size PV array is used to design SP, TCT and LS-TCT configurations for performance investigation is carried out shadow test cases.

1. Solar PV array (2x2)	PV array system	• Cell technology: Poly-Si • Dimension (mm): 356×490×25 • Manf.: Spark Solar Technologies (Model: Model: SS2018P)	
	Artificial solar lamp	• Total number of lamps- 16(4x4) • A potentiometer • Light intensity 50- 650W/m²	• Solar lamp array (4x4) system is utilized for uniform light intensity on solar PV modules in lab. • This potentiometer is integrated with lamp system to govern light intensity for the experimental study under variable shadow test cases.
2. Performance measurement system	Multi-meter used as voltmeter	• Number of voltage meter: 1 • Measurement range: 0.01 to 1000V DC. • Manf: Scientech Technology	• Measurement of voltage of SP, TCT and LS-TCT configurations under different test cases.
	Multi-meter used as Ammeter	• No. of current meter: 1 • Measurement range: 0.01 to 10A DC • Manf: Scientech Technology	• Measurement of current of SP, TCT and LS-TCT configurations under different test cases.
	Decade resistive load	• Range: 0.1 to 1 MΩ • Manf: Nvis Technology	• Variable load (decade resistive box) is used to characterise the solar PV system from 0 Ω to maximum required load accordingly.

3. PV System Technology

3.1. Mathematical modelling

The demonstrated electrical-equivalent circuit in Figure 3 of solar cell represents the ability to transform sunlight into dc current and voltage through PV effect as,
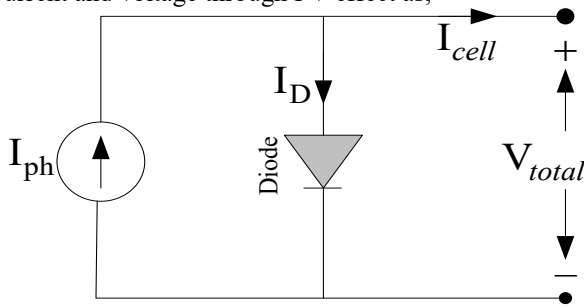

Figure 3. Equivalent circuit of solar cell

Deliberated current of solar cell (I_{cell}) can be expressed in equations as,

$$I_{cell} = I_{ph} - I_D \tag{1}$$

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

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 (°C).

3.2. Power losses and fill factor

The amount of current obtained from 2x2 size PV array is based on the sun irradiance and expressed in Eq. (3) as,

$$I = \left(\frac{S_x}{S_{STC}} \right) \times I_m \tag{3}$$

Where, I_m is the maximum current generated by PV module at standard test condition irradiation (S_{STC}) of 1000W/m² and S_x is actual irradiation on PV module surface. PV array voltage can be evaluated using Eq. (4) as,

$$V = \sum_{n=1}^{2} V_{mn} \tag{4}$$

where, V_{mn} is the generated maximum voltage of nth row of the solar PV array system.

The evaluation of power loss of solar PV system is shown in Eq. (5) as,

Power loss = Maximum power at without shadow – GMP under partial shadow (5)

The power loss is major cause of changes in FF for PV array. The relation for FF is dependent upon O.C. voltage (V_{oc}) and S.C. current (I_{sc}) of PV array. The FF will be affected with the

variation in the shadow locations and can be obtained using Eq. (6) as,

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \quad (6)$$

Moreover, the expression for power gain (PG) is shown in Eq. (7). The PG evaluation for the all the considered configurations with respect to SP configuration under three shadow test cases is carried out and depicted in table 3 as,

$$P_{Gain} = 100 - \left(\frac{P_{Loss} \times 100}{P_{LossSP}} \right) \quad (7)$$

Table 2. Power gain for TCT and LS-TCT configurations with respect to SP configuration

Shading case	TCT	LS-TCT
Shading case-1	18.38%	5.46%
Shading case-2	-0.44%	32.97%
Shading case-3	0.75%	0.32%
Average power gain (%)	**6.23%**	**12.92%**

The electrical connections of PV modules are can be considered as series and/or parallel to achieve higher range of current and voltage. The schematic diagram of SP, TCT and LS-TCT configurations are shown in Figure 4(a)-(c) as,
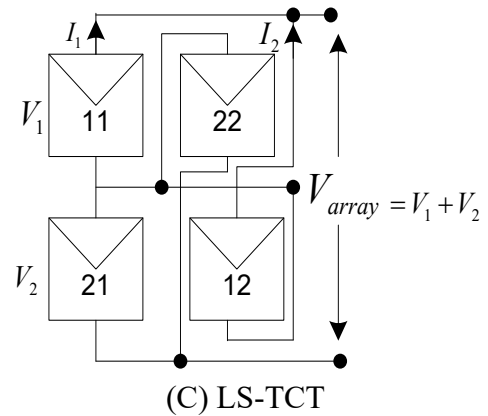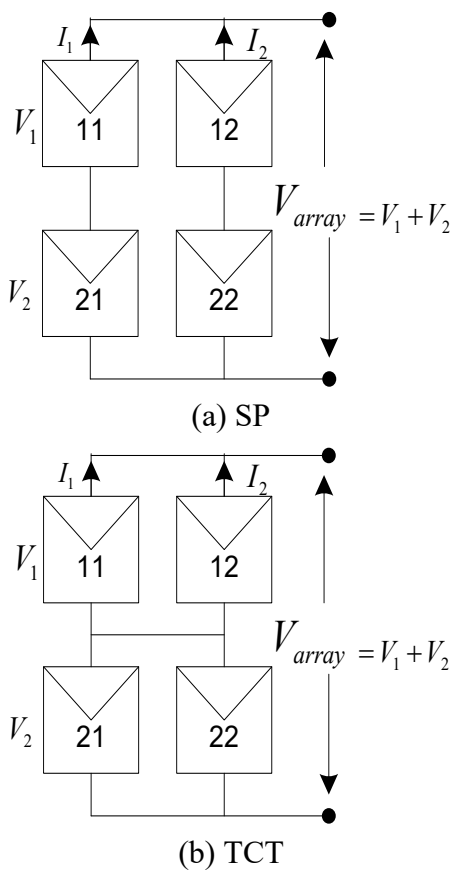

(a) SP

(b) TCT

(C) LS-TCT

Figure 4. Schematic diagram of PV array configuration

4. Shadow test cases analysis

The considered three shadow test cases acknowledged in this paper viz. First: single PV module-11 shaded; Second: two PV modules shaded- 11and 12; Third: three PV modules shaded- 11, 12 and 22 due to the movement of the sun or any type of obstruction. The article briefly reflects the impact of these considered all shadow cases-1, 2, 3 on solar PV performance in terms of minimum power losses, GMPP locations and improved FF. Patterns of three shading cases are shown in Figure 5 as,
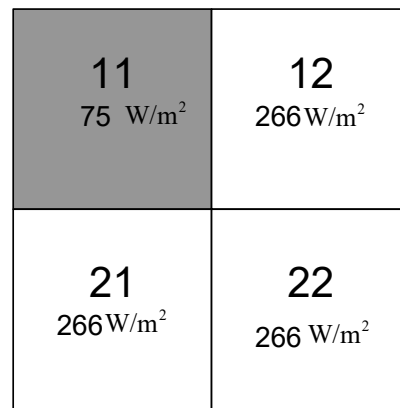
(a) Case-1
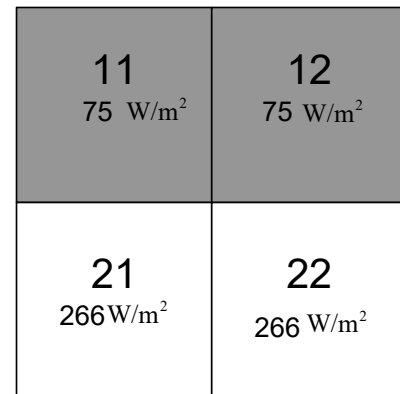
(b) Case-2

11 75 W/m²	12 75 W/m²
21 266 W/m²	22 75 W/m²

(c) Case-3

Figure 5. Shadow test cases for performance evaluation

In shading case- 1, as the three PV modules at locations 12, 21 and 22 receive the same sun irradiation as 266W/m² but one PV module at location 11 receives low irradiation as 75W/m² and treated as shaded.

(i) Current generated for shadow case-1

$$I_{R1} = \left(\frac{S}{S_{STC}}\right)I_m + \left(\frac{S}{S_{STC}}\right)I_m = \left(\frac{75}{1000}\right)\times I_m + \left(\frac{266}{1000}\right)I_m = 0.341 I_m$$

$$I_{R2} = \left(\frac{266}{1000}\right)\times I_m + \left(\frac{266}{1000}\right)I_m = 0.532 I_m$$

(8)

(ii) Current generated for shadow case-2

$$I_{R1} = \left(\frac{S}{S_{STC}}\right)I_m + \left(\frac{S}{S_{STC}}\right)I_m = \left(\frac{75}{1000}\right)\times I_m + \left(\frac{75}{1000}\right)I_m = 0.15 I_m$$

$$I_{R2} = \left(\frac{266}{1000}\right)\times I_m + \left(\frac{266}{1000}\right)I_m = 0.532 I_m$$

(9)

(iii) Current generated for shadow case-3

$$I_{R1} = \left(\frac{S}{S_{STC}}\right)I_m + \left(\frac{S}{S_{STC}}\right)I_m = \left(\frac{75}{1000}\right)\times I_m + \left(\frac{75}{1000}\right)I_m = 0.15 I_m$$

$$I_{R2} = \left(\frac{266}{1000}\right)\times I_m + \left(\frac{75}{1000}\right)I_m = 0.341 I_m$$

(10)

The theoretical values of current, voltage and power of SP, TCT and LS-TCT configurations of PV array for shading cases can be assessed similarly.

5. Results and discussion

An extensive study is done to show the reflection of shadowing cases- 1, 2 and 3 on PV array configurations such as SP, TCT and LS-TCT. For the characterization of 2×2 size solar PV system, the maximum irradiation level is kept as 266 W/m² (for non-shading condition) and minimum irradiation level is taken as 75W/m² (for shading condition). The outcomes of this present study as follows,

- Characterization of 2×2 size solar PV system without shadow
- Performance characteristics of PV system under shadow test cases-1,2,3

5.1. Characterization of 2x2 size solar PV system without shadow

P-V and I-V characteristics of 2×2 size PV system under uniform irradiation condition is observed as I_{SC} and V_{OC} are given as 0.532A and 36.8V respectively. Moreover, maximum power is generated as 13.34W. The electrical performance curves are shown in Figure 6 as,
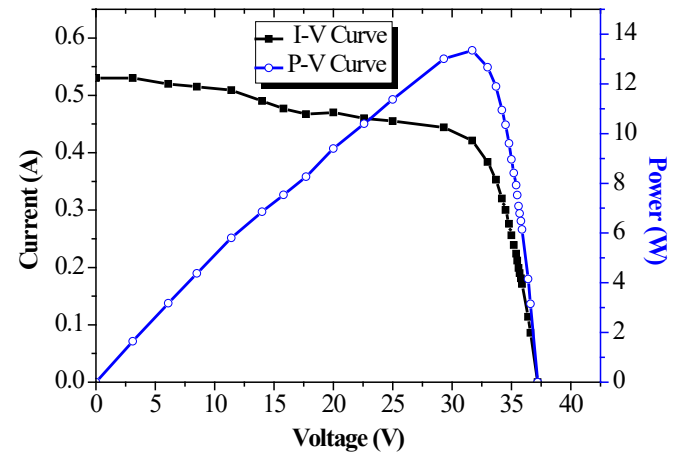

Figure 6. I-V and P-V curves of solar PV array under non-shading condition

5.2. Performance characteristics of PV system under shadow test cases-1, 2 and 3

Under the shadow case-1, obtained I-V and P-V curves for SP, TCT and LS-TCT configurations of PV array system are depicted in Figure 7(a)-(b). Performance behaviour is compared among the I-V curves and observed that maximum current (I_m) are found maximum for TCT and LS-TCT configurations as 0.304A and 0.283A respectively. Furthermore, SP has minimum value of current as 0.280A. Moreover, two MPPs such as local and global MPPs are found on the P-V curves for each PV array configuration. Under shadowing case-1, global MPP for TCT has maximum value as 9.789W and compared with GMPPs of SP and LS-TCT as 8.988W and 9.226W respectively. Performance parameters such as minimum power loss and improved FF are found best as 3.557W and 0.551 for TCT configuration and compared with lower performance of SP, LS-TCT configurations.
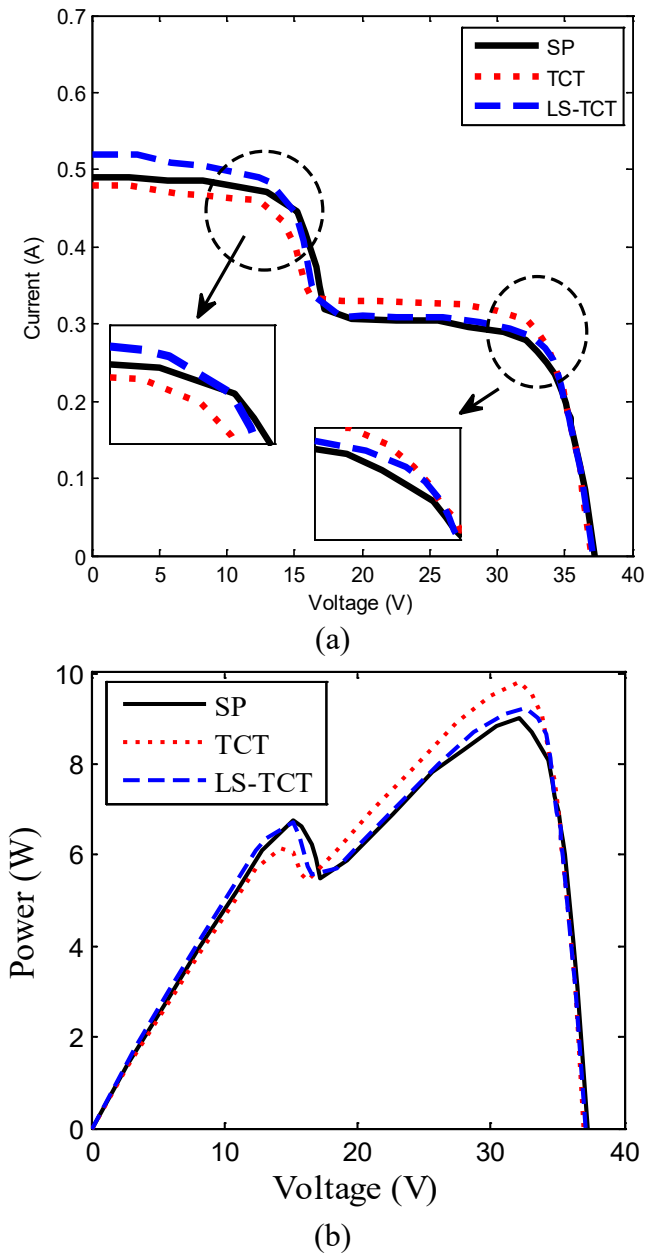
(a)

(b)

Figure 7. (a) I-V **(b)** P-V curves of SP, TCT and LS-TCT solar PV array under shading case-1

lower performance of SP, TCT configurations in terms of minimum power loss and FF as 4.731W and 0.733 respectively.
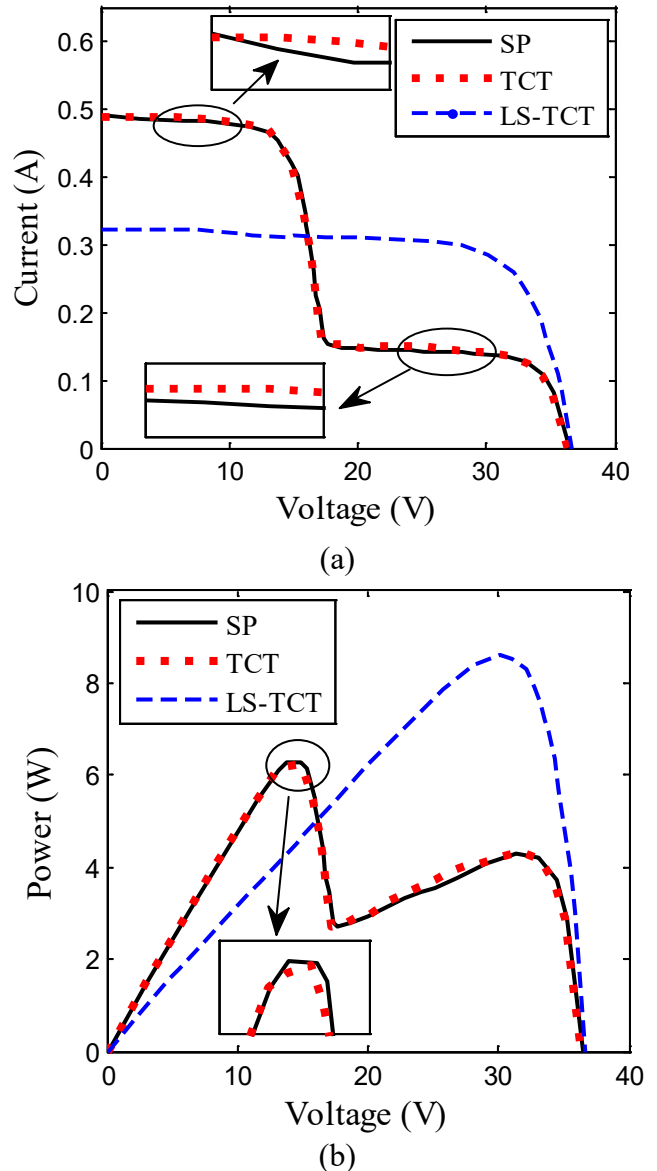

(a)

(b)

Figure 8. (a) I-V **(b)** P-V curves of SP, TCT and LS-TCT solar PV array under shading case-2

Obtained I-V and P-V curves for SP, TCT and LS-TCT configurations of PV array under shadow test case-2 are shown in Figure 8(a)-(b). The performance is compared among the obtained I-V curves and I_m is obtained for SP configuration as 0.455A and for both TCT, LS-TCT configurations have minimum values of current as 0.425A and 0.286A respectively. Moreover, two MPPs such as local and global MPP are found as 6.279W and 6.248W respectively on the P-V curves for SP and TCT configurations. Moreover, LS-TCT has maximum value at single MPP as 8.609W. Furthermore, performance parameters of LS-TCT are found best and compared with

Electrical performance curves such as I-V and P-V for SP, TCT and LS-TCT configurations of PV array under shadowing case-3 are depicted in Figure 9(a)-(b). I-V curves of each configuration have compared and I_m is found higher side for SP, LS-TCT configurations as 0.292A. For TCT configuration has minimum values of I_m as 0.142A. Moreover, two MPPs such as local and global MPPs are found on the P-V curves for each configuration. In shadowing case-3, TCT has maximum value at GMPP as 4.274W as compared SP and LS-TCT configurations as 4.205W and 4.235W respectively. Furthermore, performance parameters of TCT configuration are found better and compared with

lower performance of SP and LS-TCT configurations in terms of minimum power loss and improved FF as 9.072W, 0.385 respectively.
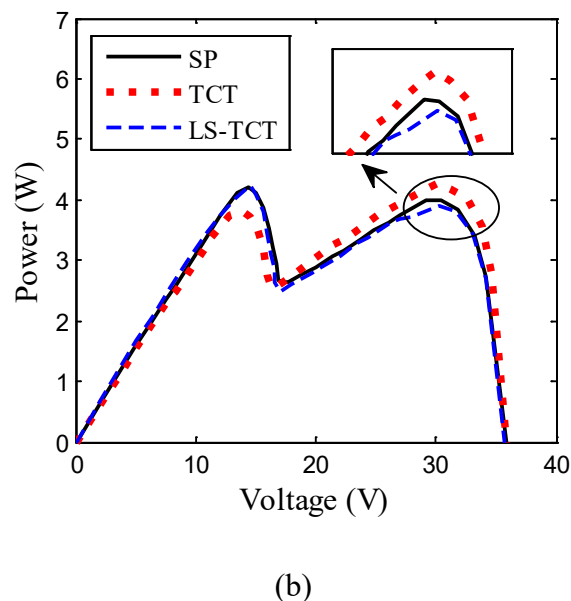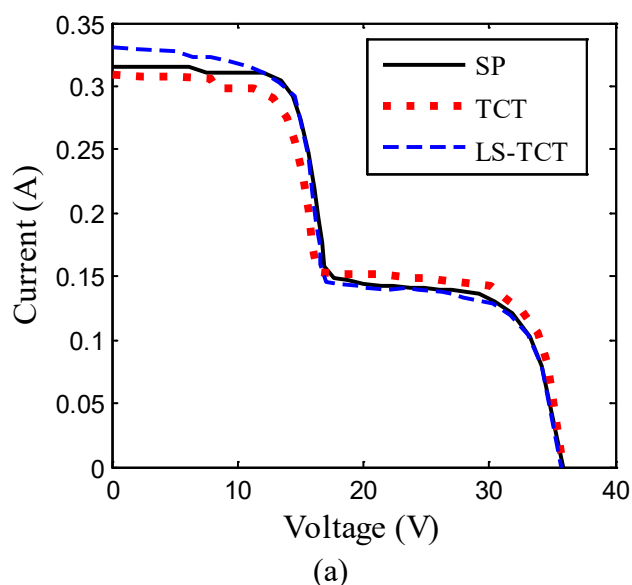

(a)

(b)

Figure 9. (a) I-V **(b)** P-V curves of SP, TCT and LS-TCT solar PV array under shading case-3

A statistically based detailed comparison of all important performance parameters, such as voltage and power at GMPP, power loss and FF of all configurations under shadow test cases, is rendered and graphically shown in Figure 10(a)-(d). Moreover, the quantitative analysis of entire performance parameters of PV system is depicted in Table-3 as,

Table 3. Performance parameters of SP, TCT and LS-TCT configurations under shadow cases

Electrical parameters	SP	TCT	LS-TCT
Shadowing case-1			
O. C. voltage (V_{OC}) (V)	37.2	37	37.1
S. C. current (I_{SC}) (A)	0.49	0.48	0.52
Maximum voltage (V_{max})	32.1	32.2	32.6
Maximum current (I_m)	0.28	0.304	0.283
Power at GMPP (W)	8.988	9.789	9.226
Mismatch power (W)	2.224	3.626	2.521
Power loss (W)	4.358	3.557	4.12
Fill factor	0.493	0.551	0.478
Shadowing case-2			
O. C. voltage (V_{OC}) (V)	36.5	36.3	36.6
S. C. current (I_{SC}) (A)	0.49	0.489	0.321
Maximum voltage (V_{max})	13.8	14.7	30.1
Maximum current (I_m)	0.455	0.425	0.286
Power at GMPP (W)	6.279	6.248	8.609
Mismatch power (W)	1.977	1.918	0
Power loss (W)	7.067	7.098	4.737
Fill factor	0.351	0.352	0.733
Shadowing case-3			
O. C. voltage (V_{OC}) (V)	35.8	35.9	35.7
S. C. current (I_{SC}) (A)	0.315	0.309	0.33
Maximum voltage (V_{max})	14.4	30.1	14.5

Maximum current (I_m)	0.292	0.142	0.292
Power at GMPP (W)	4.205	4.274	4.234
Mismatch power (W)	0.204	0.452	0.338
Power loss (W)	9.141	9.072	9.112
Fill factor	0.373	0.385	0.359
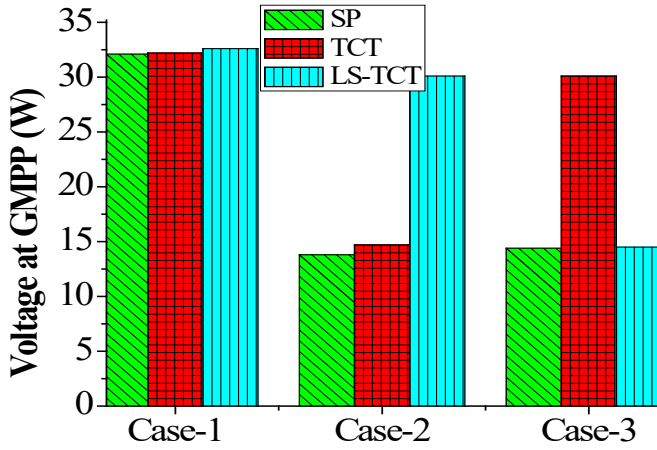
(a) Voltage at GMPP
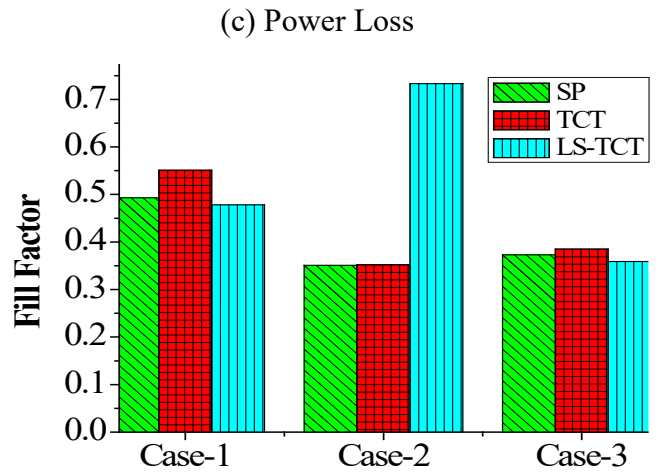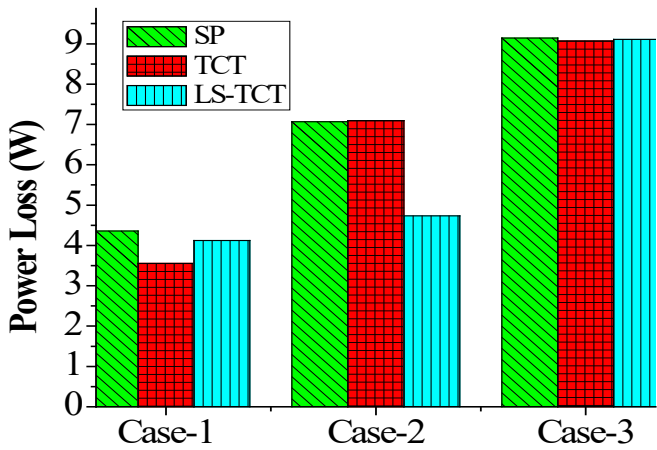

(b) Power at GMPP

(c) Power Loss
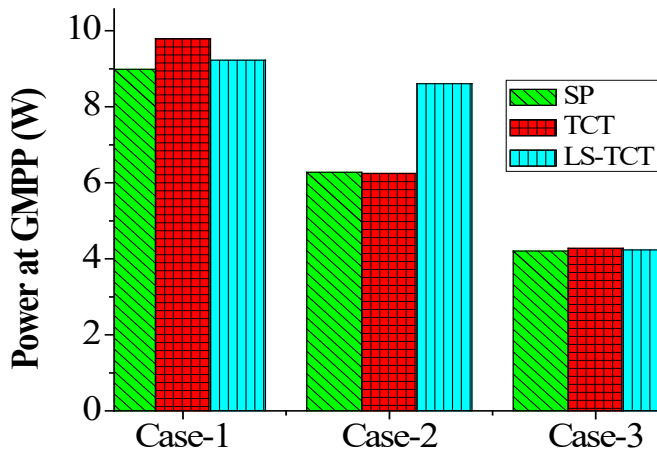
(d) FF

Figure 10. Comparison of performance parameters

6. Conclusion

In this paper, an experimental study on the performance of Poly-crystalline solar PV panels is considered in three shadow test cases. The experiment was performed without a shading effect to describe the P-V and I-V curves of four numbers of PV panels arranged in a 2×2 string of forms such as SP, TCT and LS-TCT connections. The electrical connections of the SP configured PV array system are compared to the TCT and LS-TCT configurations for performance comparison. Experimental results of TCT and LS-TCT are found better for all the shadow test cases in terms of power at GMPP (for TCT: 9.789W, 4.274W and for LS-TCT: 8.609W), minimum power losses (for TCT: 3.557W, 9.072W and for LS-TCT: 4.737W) and improved FF (for TCT: 0.551, 0.385 and for LS-TCT: 0.733). The obtained results confirm the impact of shading phenomenon for performance validation of PV system and their electrical connections.

Acknowledgements

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