

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

Arthur Bleicher<sup>1</sup>, Rupendra Pachauri<sup>2,\*</sup>, Piyush Kuchhal<sup>3</sup> and Kamal Bansal<sup>2</sup>

<sup>1</sup>ECAM-EPMI, Cergy-Pontoise- 95092, France

<sup>2</sup>Department of Electrical and Electronics Engineering, School of Engineering, University of Petroleum and Energy Studies, Dehradun, India- 248007

<sup>3</sup>Applied Science Department, School of Engineering, University of Petroleum and Energy Studies, Dehradun, India- 248007

### 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.

**Keywords:** photovoltaic system, partial shadow, latin square, global maximum power point.

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### 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

\*Corresponding author. Email: rpachauri@ddn.upes.ac.in

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].

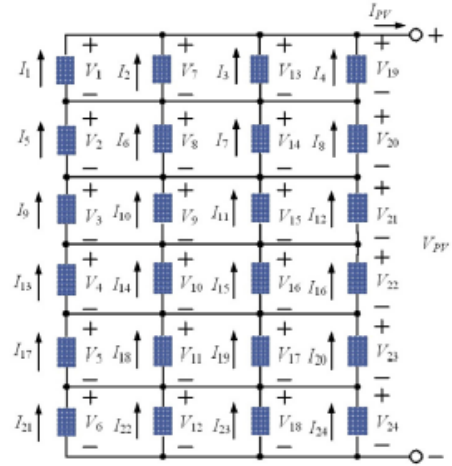
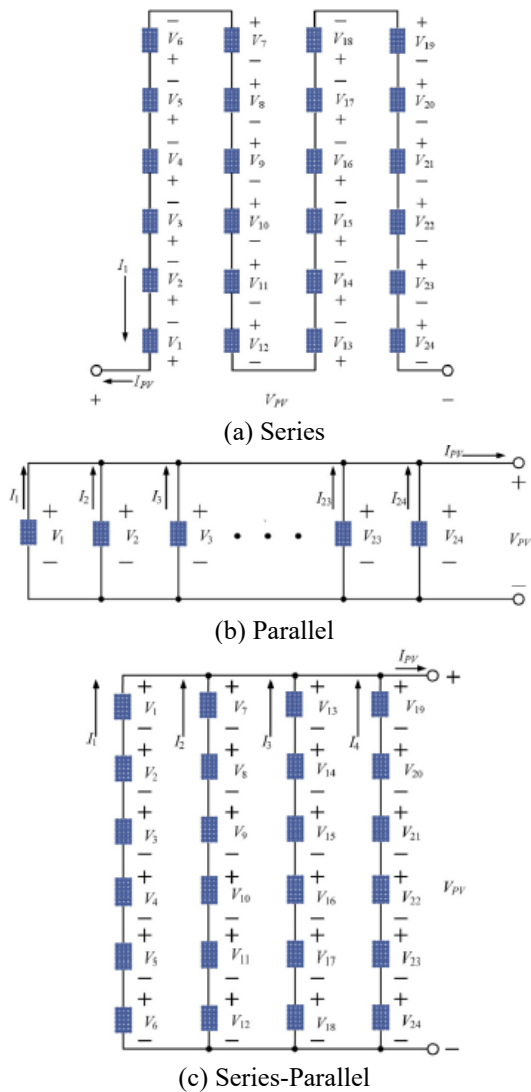
## 1.1. Conventional PV array configurations

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

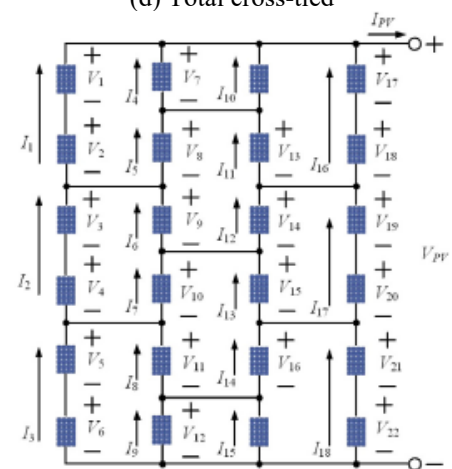
- **Series Array:** PV modules are connected in series as shown in Figure 1(a). That enhances array voltage performance for load application.
- **Parallel Array:** As shown in Figure 1(b), PV modules are connected in parallel. This type of PV module electrical connection increases the current array performance.
- **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.

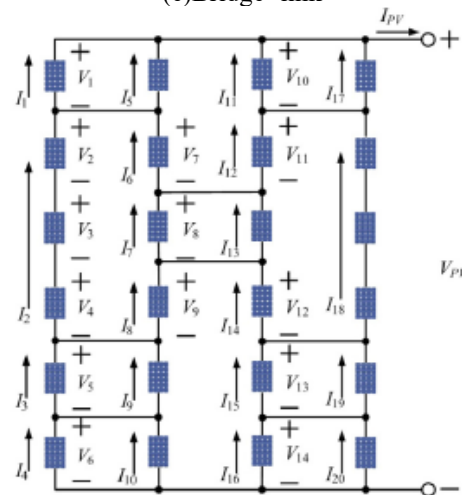
- **Bridge-Link Array:** A bridge architecture is used to connect PV modules as shown in Figure 1(e). If configurations of this kind are partially shaded, it will also affect the neighbouring modules, raising the total voltage and current output.
- **Honeycomb Array:** In a honeycomb configuration, PV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



(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.

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,

## 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

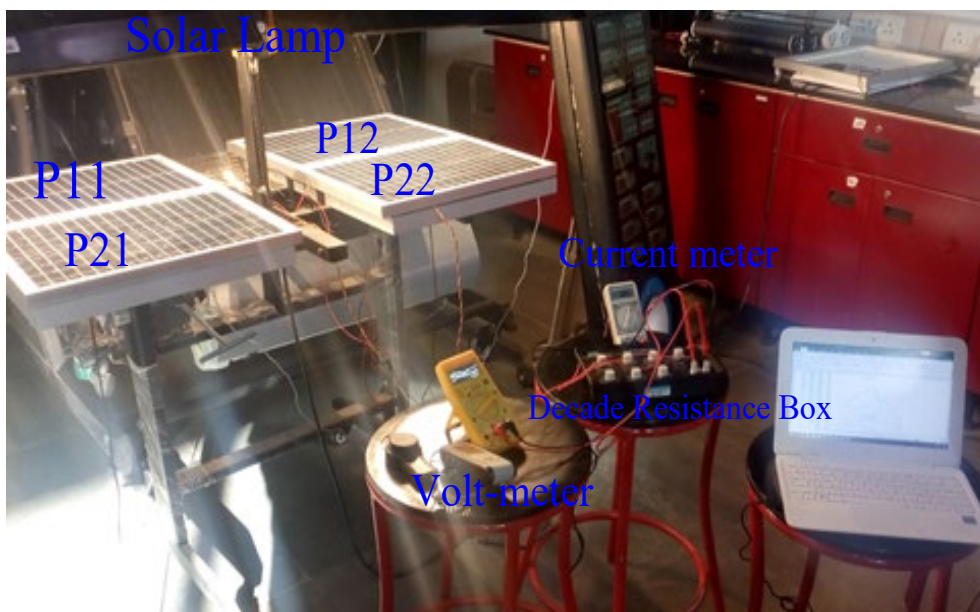


Figure 2. Experimental set-up

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

Section	Components	Specifications	Role/function
		<ul style="list-style-type: none"> <li>• PV array power: 20 W</li> <li>• O. C. voltage: 22.58 V</li> <li>• S. C. current: 1.19 A</li> <li>• <math>I_{mpp}</math>: 1.08A, <math>V_{mpp}</math>: 18.82V</li> <li>• No. of PV module: 4 (2x2 array)</li> </ul>	<ul style="list-style-type: none"> <li>• 2x2 size PV array is used to design SP, TCT and LS-TCT configurations for performance investigation is carried out shadow test cases.</li> </ul>

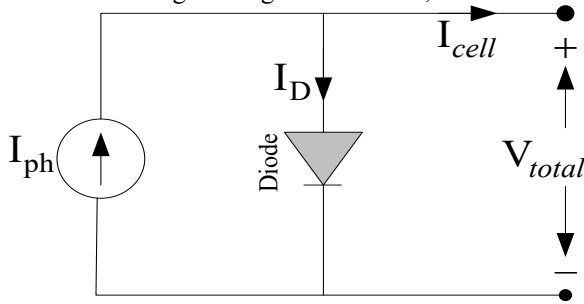


1. Solar PV array (2x2)	PV array system	<ul style="list-style-type: none"> <li>Cell technology: Poly-Si</li> <li>Dimension (mm): 356×490×25</li> <li>Manf.: Spark Solar Technologies (Model: SS2018P)</li> </ul>	
	Artificial solar lamp	<ul style="list-style-type: none"> <li>Total number of lamps- 16(4x4)</li> <li>A potentiometer</li> <li>Light intensity 50- 650W/m<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>Solar lamp array (4x4) system is utilized for uniform light intensity on solar PV modules in lab.</li> <li>This potentiometer is integrated with lamp system to govern light intensity for the experimental study under variable shadow test cases.</li> </ul>
2. Performance measurement system	Multi-meter used as voltmeter	<ul style="list-style-type: none"> <li>Number of voltage meter: 1</li> <li>Measurement range: 0.01 to 1000V DC.</li> <li>Manf: Scientech Technology</li> </ul>	<ul style="list-style-type: none"> <li>Measurement of voltage of SP, TCT and LS-TCT configurations under different test cases.</li> </ul>
	Multi-meter used as Ammeter	<ul style="list-style-type: none"> <li>No. of current meter: 1</li> <li>Measurement range: 0.01 to 10A DC</li> <li>Manf: Scientech Technology</li> </ul>	<ul style="list-style-type: none"> <li>Measurement of current of SP, TCT and LS-TCT configurations under different test cases.</li> </ul>
	Decade resistive load	<ul style="list-style-type: none"> <li>Range: 0.1 to 1 MΩ</li> <li>Manf: Nvis Technology</li> </ul>	<ul style="list-style-type: none"> <li>Variable load (decade resistive box) is used to characterise the solar PV system from 0 Ω to maximum required load accordingly.</li> </ul>

### 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,

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

$$I_{cell} = I_{ph} - I_o \left( \exp \left( \frac{qV_c}{AKT_c} \right) - 1 \right) \quad (2)$$

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 (°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,

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

Where,  $I_m$  is the maximum current generated by PV module at standard test condition irradiation ( $S_{STC}$ ) of 1000W/m<sup>2</sup> and  $S_x$  is actual irradiance on PV module surface. PV array voltage can be evaluated using Eq. (4) as,

$$V = \sum_{n=1}^2 V_{mn} \quad (4)$$

where,  $V_{mn}$  is the generated maximum voltage of n<sup>th</sup> row of the solar PV array system.

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

$$\text{Power loss} = \text{Maximum power at without shadow} - \text{GMP under partial shadow} \quad (5)$$

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



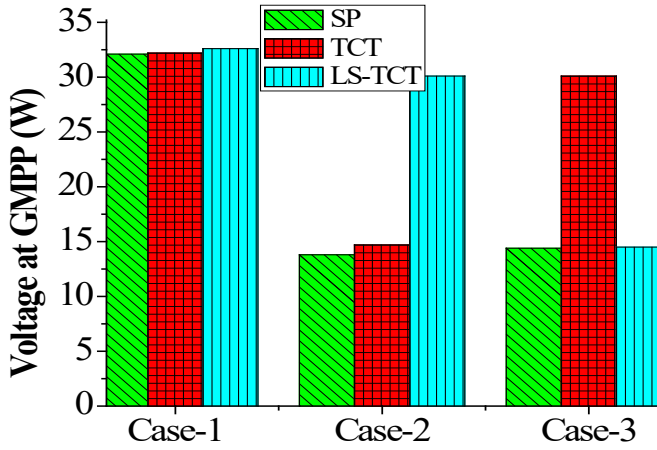




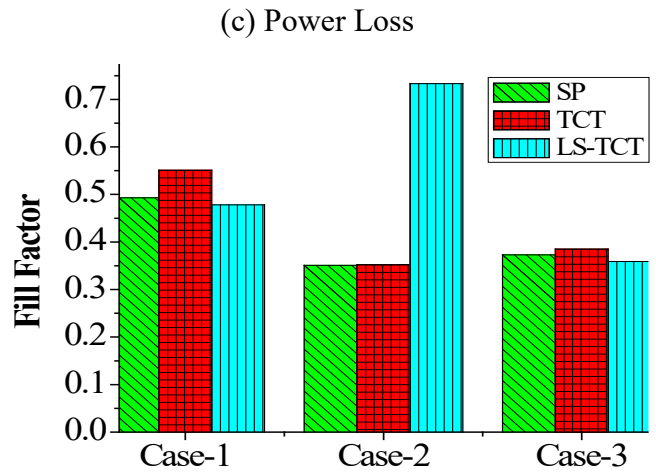




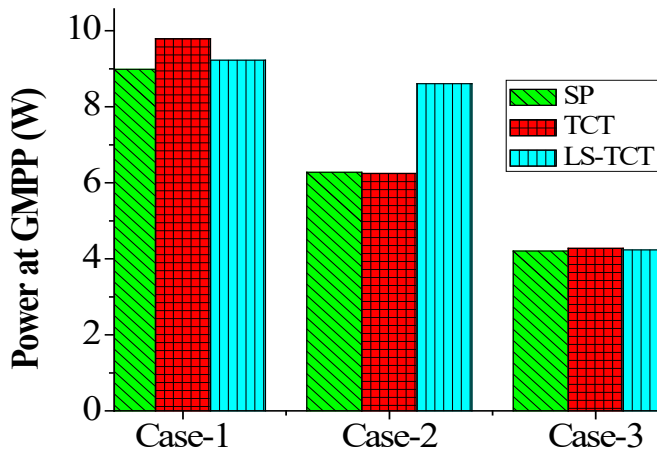
Maximum current ( $I_m$ )	0.292	0.142	0.292
Power at GMPP (W)	4.205	4.274	4.234
Mismatch power (W)	0.204	0.452	0.338
Power loss (W)	9.141	9.072	9.112
Fill factor	0.373	0.385	0.359



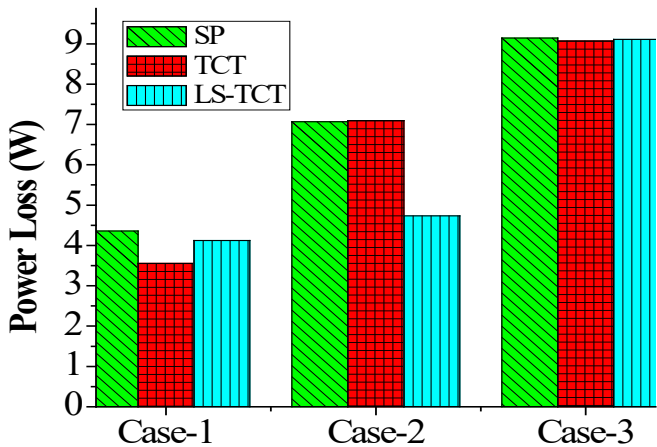
(a) Voltage at GMPP



(c) Power Loss



(b) Power at GMPP



(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 2x2 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.

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