Investigation of Power losses on Solar Photovoltaic Array Interconnections Under Mismatch Conditions

Sai Krishna G¹ · Tukaram Moger¹

Received: 19 February 2021 / Accepted: 13 September 2021 / Published online: 14 October 2021
 © The Author(s), under exclusive licence to Springer Nature Singapore Pte Ltd. 2021

Abstract

The mismatch effect creates a difference between the sum of maximum power generated by individual Photovoltaic (PV) modules and the overall PV array power output. Mismatch effects can be classified into internal and external mismatch effects. Internal mismatch effect occurs because of factors such as manufacturing defects and ageing. The external effect occurs because of variations in solar irradiance and temperature. This paper presents the investigation of internal and external mismatch effects on various 5×4 Photovoltaic (PV) array interconnections such as series-parallel, total-cross-tied, bridge-link, honey-comb, hybrid SP-TCT, hybrid BL-TCT, along with proposed hybrid HC-TCT and hybrid HC-BL. Six mismatch case studies are considered in this paper to investigate the performance of PV array connections. Among the six cases, three cases are due to internal mismatch effects, and the remaining three cases belong to the external effects. In addition, the global maximum power point (GMPP), the voltage at GMPP, thermal voltage, power loss, fill-factor, efficiency (η), and possible local peaks (PLP) parameters are calculated and compared for each PV array connection under all case studies using Matlab-Simulink. Also, for each PV array connection, the revenue generation is calculated from energy savings under mismatch effects. The paper summary shows that TCT, HC-TCT, and HC-BL array connections delivered beneficial results under external effects, and TCT, HC, HC-TCT, and HC-BL provided superior results under internal effects.

Keywords PV array modelling · Partial shadings · Global power output · PV array connections · PV efficiency

Notations

G : Actual irradiance of PV module
 I_d : Diode current
 I_{sh} : Shunt current of a PV cell
 I_{cell}/I_{pv} : PV cell/ module current (A)
 a : Ideality factor
 n_s : PV cells connected in series
 N_S : Series connected PV modules
 N_P : Parallel connected PV modules
 P_{MPP} : Maximum power at uniform condition
 q : Electron charge 1.6×10^{-19} C
 R_S : Series resistance of a PV module
 R_P : Shunt resistance of a PV module
 T_c : Operating temperature of a PV cell
 V_{cell}/V_{pv} : PV cell/ module voltage (V)

V_d : Voltage across the diode
 V_{TH} : Thermal voltage
 η : Efficiency

Introduction

Nowadays, PV technology is advancing rapidly, with module efficiency increasing and manufacturing cost decreasing. These facts show that PV technology is approaching maturity [1, 2]. However, even with today's more advanced manufacturing techniques, the mismatch between identical design solar cells appears to be a minor flaw that cannot readily overcome. The differences in the electrical characteristics of solar cells result in mismatch failures within the PV module. Modules with distinct electrical characteristics result in a mismatch in the entire PV plant. According to the literature, the mismatch effects classified into internal and external mismatch effects [3, 4].

Internal mismatch effects are caused because of non-identical properties of solar cells, such as series resistance (R_S), shunt resistance (R_P), ideality factor (a), light generated current (I_L), and diode saturation current (I_o).

✉ Sai Krishna G
 saikrishna240@gmail.com

¹ Department of Electrical & Electronics Engineering,
 National Institute of Technology, Karnataka 575025, India

According to the literature [5], the probability of R_s , R_{sh} and a parameters mismatch is high at the time of manufacturing. External mismatch effect occurs because of unequal solar irradiance and temperature of the PV module. Unequal solar irradiance is called the partial shading condition (PSC). Partial shading happens when telephone towers and passing clouds cover some part of the PV array. In PSCs, the shaded part receives less solar irradiance than the unshaded part [6]. This results in the hot-spot effect in a PV module, which damages the PV cell or module. An approach to protect the shaded PV modules from harm is by connecting bypass diodes across the terminals. The incorporation of diodes results in multiple peaks in the P–V characteristics. Among multiple peaks, one global peak, which generates the highest maximum power, is recognized as a global maximum power point (GMPP). Because of numerous peaks, the MPPT can skip the GMPP. This results in an additional power loss in the PV system, and a reduction technique is required to mitigate these losses. According to the literature, many solutions have been reported to reduce losses resulting from PSCs. The most prevalent solution is the PV array interconnection [7, 8].

Literature Survey

Various types of PV array connections have been reported in the literature to reduce mismatch losses caused by partial shading, such as “simple-series (SS), parallel (P), series-parallel (SP), total-cross-tied (TCT), bridge-link (BL), and honey-comb (HC)” [9]. In [10], the authors considered SP, TCT and BL PV arrays for reliability evaluation using the probabilistic approach under mismatch issues due to manufacturing tolerance. This paper indicates that the interconnection between PV modules (i.e., TCT and BL) can increase the operational lifetime by 30% as compared to SP PV array. The authors also examine the performance of array interconnections under partial shading and ageing conditions by obtaining the maximum power, fill-factor (FF) and power loss (PL) [11, 12]. The results conclusively established that TCT array shows superior performance as compared to SP and BL PV arrays. In [9], developed a numerical model based on Newton-Raphson method for plotting the I–V and P–V characteristics for different PV array interconnections such as; “SS, SP, TCT, BL and HC”. In this study, the authors observed that TCT array produced the highest maximum power as compared to the other interconnections. In [13], investigated the performance of 5×4 “SS, P, SP, TCT, BL and HC” PV array interconnections under various PSCs. The results indicated that the TCT PV array exhibited the best performance in most cases of partial

shadings. In [14], developed an optimum TCT PV array by assuming that this problem as a mixed integer non-linear programming problem could be solved using the branch and bound (BB) algorithm to reduce irradiance mismatch index (IMI). In this approach, the location of shaded PV modules shifted from one row into other rows to increase global maximum power. Subsequently, the same authors proposed an optimal reconfiguration approach for TCT PV array to mitigate the PSCs [15]. In this approach, the shaded PV modules are shifted from one column to another using electrical switches to distribute the PSCs. In [16], authors proposed SuDoKu and Optimal SuDoKu PV array arrangements for TCT PV array to reduce mismatch losses and increase global maximum power under PSCs. In this study, the physical location of PV modules are rearranged based on the proposed methods to distribute the shading effects over the array. In [17], developed a novel 5×5 PV array interconnection and compared the performances of existing interconnections under PSCs. The performance of each connection is obtained by considering various parameters. The result shows that the proposed interconnection enhanced the global maximum power as compared to the existing PV arrays. In [18], authors investigated the performance of 5×4 “SS, P, SP, TCT and BL” PV arrays interconnection under partial shading and faulty conditions. In this study, the authors adopted seven indicators to assess the performance of each connection using MATLAB-SIMULINK model. The results showed that TCT and BL interconnections enhanced the global maximum power and fill-factor as compared to other connections. In [8], authors conducted a comparative study on 6×6 PV array by interconnecting the PV modules in various fashions like “SS, SP, TCT, BL, and HC” under different shading patterns. In this study, the authors assumed row, column and diagonal shading patterns for appraising the performance of each PV array. The results revealed that the TCT PV array overcomes the mismatch loss under most shading patterns. A similar approach is presented in [19]. In this paper, the authors incorporated a parallel interconnection with other array interconnections to assess the performance on a 5×5 PV array. The results indicated that TCT PV array provided better results than other PV array interconnections under PSCs. The same authors investigated the effect of mismatch losses on SS, SP, and HC PV array interconnections [20]. The results proved that the PV array mismatch loss is directly proportional to the number of modules connected in series. The HC interconnection has less number of series connections; therefore, the mismatch loss is limited compared to SS and SP. In addition to existing connections, the hybrid PV array connections such as hybrid SP–TCT and BL–TCT are introduced to address PS problem [21].

Table 1 Summary of modelling of various PV array interconnections under the external mismatch effect

Authors	PV array configurations	Array level	Simulink or Experimental	power output	Shading cases	Remarks
[22]	“SP”	4 × 4 module array	simulink	350 W	horizontal, vertical and diagonal	partial shading analysis done for SP array only
[23]	“SP, TCT”	3 × 3 cell array	both	200 W	group of rows and columns	partial shading analysis done for SP, TCT array
[24]	“SP, TCT”	3 × 3 module array	simulink	600 W	horizontal and vertical	PV modules connection matrix is developed to change the configuration
[15]	“SP, TCT”	6 × 4 module array	simulink	3800 W	row and column modules	authors considered SP and TCT configuration for PSCs
[25]	“SP, TCT, BL”	3 × 3 module array	simulink	1500 W	row and column modules	partial shading analysis performed on small array level
[9]	“SS, SP, TCT, BL and HC”	6 × 6 cell array	simulink	40 W	horizontal, vertical and diagonal	authors investigated the study under uniform condition
[5]	“SP, TCT, BL”	36 × 8 cell array	simulink	400 W	various shading conditions	they have analysed only small array levels
[17]	“SS, SP, TCT, BL and HC”	6 × 4 module array	simulink	4800 W	SW,LW,SN,LN	authors developed simulink model only for small array levels
[19]	“SS, P, SP, TCT, BL and HC”	5 × 5 module array	simulink	6000 W	SW,LW,SN,LN	authors developed simulink model only for small array levels
[20]	“SS, SP, HC”	5 × 5 module array	simulink	6000 W	SW,LW,SN,LN	authors modelled array configurations only for SS,SP and HC
[26]	“SS, P, SP, TCT, BL and HC”	6 × 6 module array	simulink	5000 W	SW,LW,SN,LN	authors considered only six array configurations
[13]	“SS, P, SP, TCT, BL and HC”	6 × 4 module array	simulink	4800 W	vertical up and down	authors considered only six array configurations
[27]	“SS, SP, TCT, BL”	5 × 5 module array	simulink	6000 W	SW,LW,SN,LN	authors performed shading study for four array configurations
[18]	“SS, P, SP, TCT, BL”	6 × 4 module array	simulink	5800 W	vertical up and down shadings	authors developed simulink model for only five array configurations
[28]	“SP, TCT, BL”	3 × 3 module array	simulink and experimental	350 W	horizontal and vertical shadings	authors considered only three array configurations
[29]	“SS, P, SP, TCT, BL, HC”	8 × 4 module array	simulink and experimental	9000 W	horizontal and vertical shadings	authors developed simulink model for conventional configurations

According to literature, the influence of external mismatch effects on conventional (i.e., SP, TCT, BL, HC) and hybrid PV arrays (i.e., SP-TCT, BL-TCT) is addressed in multiple papers, which are reported in Table 1. Additionally, it is identified that, the effect of PSCs is investigated on smaller PV array sizes, such as 3×3 , 4×3 , 4×4 , and 5×4 using Simulink platform. However, according to the authors understanding, the modelling and assessment of conventional and hybrid interconnections under internal mismatch effects have not yet been explored in literature. Therefore, this paper presents the impact of internal and external mismatch losses on the conventional and hybrid PV array interconnections such as “SP, TCT, BL, HC, and SP-TCT, BL-TCT”, respectively. In addition to this, two new hybrid PV array interconnections, i.e., HC-TCT and HC-BL are proposed to investigate the mismatch loss along with other interconnections. Six case studies are considered to review the performance on 5×4 PV array. In six cases, three of them are due to an internal mismatch effect, and the remaining three belongs to the external mismatch effect. Besides, the global maximum power point (GMPP), voltage at GMPP (V_{GMPP}), thermal voltage (V_{TH}), power loss (PL), fill-factor (FF), efficiency (η) and possible local peaks (PLP) parameters are obtained and compared for each array interconnection under all case studies.

Figure 1 describes the entire structure of this paper, including PV array connections, case studies, and parameters for the investigation. The rest of the paper is organized as follows; Section “PV array Interconnections” describes the various PV array interconnections reported in the literature. The detailed mathematical modelling of a PV array is presented in “Modelling of Photovoltaic Array”. Section “Description of Case Studies” illustrates a detailed description of case studies. Section “Results and Discussions” explains the simulation results of each PV array interconnection under mismatch effects and then followed by a conclusion in “Conclusion”.

PV array Interconnections

Two kinds of PV array connections are reported in the open literature, divided into conventional and hybrid connections.

Conventional PV Array Interconnections

As mentioned earlier in “Introduction”, various conventional PV array interconnections are reported in the literature to reduce partial shadings such as “simple-series, parallel, series-parallel, total-cross-tied, bridge-link, and honey-

Fig. 1 Various PV array topologies, case studies and acquired parameters

comb". The general layouts of PV array interconnections are shown in Fig. 2a-f. Among all, the series and parallel connections are designed based on fundamental electrical circuits. In a series connection, PV modules are connected in series to achieve higher voltage (refer in Fig. 2a), and the array current is the same as module current [30]. In parallel connection, PV modules are connected in parallel fashion to build higher current in its output (refer in Fig. 2b), and the array voltage is the same as module voltage. The advantage of parallel connection over series is that the maximum power of the parallel connection is higher than that from the series connection [31]. In series-parallel, first connect PV modules in series to form string so that the module's voltage is summed-up, and many of these strings are connected in parallel to increase the output current (refer in Fig. 2c). This connection is widely used in real-time PV plants because it is effortless to install and also economical. In TCT, connect PV modules in parallel as a row, which increases the output current, and then many rows are connected in series fashion to increase the output voltage. This connection required more wiring for installation; this would increase the cost. The SP and TCT connections produce the same power value in uniform conditions, and the TCT topology reduces the overall mismatch effect. The bridge-link connection is the

same as TCT, but half of the connections are avoided (refer in Fig. 2e), so that cable losses and wiring installation time are reduced [32, 33]. TCT and BL PV arrays are combined to form the HC connection, as shown in Fig. 2f. In this topology, the modules are interconnected similar to the hexagonal shape.

Hybrid PV array interconnections

The combination of two conventional array interconnections provides a hybrid connection. In [21], authors introduced hybrid SP-TCT and BL-TCT connections (refer in Fig. 2h and g) to examine the effect of PSCs. The SP-TCT connection is the combination of SP and TCT interconnections. Likewise, the BL-TCT connection is the combination of BL and TCT interconnections. Similarly, this paper proposed HC-TCT and HC-BL array interconnections (refer in Fig. 2i and j) to investigate the effect of mismatch.

Modelling of Photovoltaic Array

A PV cell converts sunlight into electricity (DC) based on the PV effect. A PV cell can generate 0.7 V DC and a

Fig. 2 Different PV array interconnections; (a) Simple-Series, (b) Parallel, (c) Series-Parallel, (d) Total-Cross-Tied, (e) Bridge-Link, (f) Honey-Comb, (g) hybrid BL-TCT, (h) hybrid SP-TCT, (i) hybrid HC-TCT, (j) hybrid HC-BL

Fig. 3 Circuit diagram of a single diode model

few amperes current at standard test condition (STC) [34]. PV cells are connected in series to increase the output voltage; this constitutes a PV module. For high power applications, the PV modules are connected in series and parallel, commonly called PV array. Modelling is the first step to analyse the behaviour of the PV system. The PV array modelling starts with the mathematical modelling of a single PV cell. The open-literature reported that the single diode and two diode PV cell models are widely used to study the PV system's performance. As per the literature, the single diode PV cell model is quite easy to modelling than the two diode model [13]. The single diode PV cell equivalent circuit, as shown in Fig. 3.

By applying KCL to node 'c' in Fig. 3, the I_{cell} can be written as,

$$I_{cell} = I_{L,cell} - I_d - I_{sh} \quad (1)$$

where I_d is current flowing through the diode and I_{sh} is shunt current of a PV cell,

$$I_d = I_o \left[\exp\left(\frac{V_d}{V_T}\right) - 1 \right] \quad (2)$$

$$I_{sh} = \frac{V_{cell} + I_{cell} R_s}{R_p} \quad (3)$$

$$V_T = \frac{K T_c}{q} \times a \quad (4)$$

where I_o is saturation current of PV cell at STC, which can be written as,

$$I_o = I_{do} \left[\frac{T_c}{T_{STC}} \right]^3 \left[\exp\left(\frac{q \cdot E_g}{ak}\right) \left(\frac{1}{T_{STC}} - \frac{1}{T_c} \right) \right] \quad (5)$$

where I_{do} is reverse saturation current of diode and E_g is the band gap energy,

$$E_g = 1.16 - 7.02 \times 10^{-4} \frac{T_c^2}{T_c + 1108} \quad (6)$$

The above set of equations are substituted in Eq.(1), the mathematical equation of I-V characteristics for the PV cell is given by,

$$I_{cell} = I_{L,cell} - I_o \left[\exp\left\{ \frac{q(V_{cell} + I_{cell} R_s)}{ka T_c} - 1 \right\} \right] - \left(\frac{V_{cell} + I_{cell} R_s}{R_p} \right) \quad (7)$$

R_s and R_p are the series and shunt resistances of the PV cell. PV module is composed by connecting number of solar cells in series. The mathematical representation of I-V characteristics for the PV module can be written as,

$$I_{pv} = I_L - I_o \left[\exp\left\{ \frac{q(V_{pv} + I_{pv} R_s)}{n_s k a T_c} - 1 \right\} \right] - \left(\frac{V_{pv} + I_{pv} R_s}{R_p} \right) \quad (8)$$

where I_L represents the light generated current of a module,

$$I_L = \frac{G}{G_{STC}} [I_{LSTC} + K_{isc}(T_c - T_{STC})] \quad (9)$$

It is worth noticing that Eq. 8 is a transcendental equation, and using this, one can calculate the output current of a PV module. However, Eq. 8 is not limited to single module, and can be expanded to various module connections, called an array (refer in Fig. 4). The numerical expression of I-V characteristics for the PV array is given as follows,

$$I_a = N_p \cdot I_L - N_p \cdot I_o \left[\exp\left\{ \frac{q(V_a + (\frac{N_s}{N_p}) I_a R_s)}{n_s k a T} - 1 \right\} \right] - \left(\frac{V_a + (\frac{N_s}{N_p}) I_a R_s}{(\frac{N_s}{N_p}) R_p} \right) \quad (10)$$

The above set of equations is used to model the output I-V and P-V characteristics of the PV array under both uniform

Fig. 4 Equivalent circuit model for PV array

Table 2 PV module data sheet parameters [21]

Parameters	Ratings
PV Output Power	170 watts
Open Circuit Voltage (V_{oc})	44.2 volts
Short Circuit Current (I_{sc})	5.2 amps
Current at Maximum Power (I_{mp})	4.75 amps
Voltage at Maximum Power (V_{mp})	35.8 volts
Number of Cells Connected in Series	72
Series(R_s)& Shunt(R_p) Resistance	0.52 & 162.2 ohms
Ideality factor (n)	0.96
PV Module Area	62.2inc×31.9inc

and partial shading conditions. The PV module data sheet parameters for modelling is listed in Table 2.

Description of Case Studies

Six case studies are considered to investigate the effect on various PV array interconnections under both internal and external mismatch effects. The external mismatch effects or PSCs are described in “External Mismatch Effects”.

External Mismatch Effects

Case study- E_1 is divided into five shading cases. In each case, the shadow movement of PV modules increases step by step from bottom to top in the first two columns of the array, as shown by cases I-V in Fig. 5.

Case study- E_2 is divided into five shading cases. In each case, the shadow movement of PV modules increases step by step from left to right in the last two rows of the array, as shown by cases I-V in Fig. 6.

Case study- E_3 is divided into five shading cases. In each case, the shadow movement of PV modules fluctuates up and down diagonally in the array, as shown by cases I-V in Fig. 7.

Internal Mismatch Effects

As described in “Introduction”, the probability of series resistance (R_s), shunt resistance (R_{sh}) and ideality factor (a) parameters mismatch is high in manufacturing, affecting the PV array’s power output and fill factor [12]. Three case studies are taken into account to examine the effect of internal mismatch on PV arrays. Each case, it is assumed that one of the parameters (i.e., R_s , R_p , a) varies 15% (i.e., regarded as critical degradation of PV module) of its actual value [12].

- Case study- I_1 is divided into five cases I-V. In each case, the R_s of PV modules increased to 15% of its actual value in the first two string of the 5×4 PV arrays, as shown in Fig. 8.
- Case study- I_2 is divided into five cases I-V. In each case, the R_p of PV modules decreased to 15% of its actual value in the first two string of the 5×4 PV arrays, as shown in Fig. 8.
- Case study- I_3 is divided into five cases I-V. In each case, the a of PV modules decreased to 15% of its actual value in the first two string of the 5×4 PV arrays, as shown in Fig. 8.

Description of Acquired Parameters

Fill factor

Fill-factor is an index, which measures the squareness of I-V characteristics of the PV array. This can be obtained as;

Fig. 5 Case study- E_1 for external mismatch effects

Fig. 6 Case study- E_2 for external mismatch effects

$$FF = \frac{\text{Power at GMPP}}{V_{oc} \cdot I_{sc}} \quad (11)$$

Thermal Voltage

Thermal voltage is the relationship between electrical current flow and the voltage across the PV module. This can be obtained as;

$$V_T = \frac{(2V_{mp} - V_{oc})(I_{sc} - I_{mp})}{I_{mp} - (I_{sc} - I_{mp}) \ln\left(\frac{I_{sc} - I_{mp}}{I_{sc}}\right)} \quad (12)$$

Power Losses

Power loss (PL) is the difference between the maximum power at uniform irradiance condition and the global maximum power at PSCs. This can be obtained as;

$$PL = MP_{P_{uni}} - GMPP_{PSCs} \quad (13)$$

Possible Local Peaks

In PSC, PV array exhibits multiple peaks in P-V characteristics. Only one global peak (GP) exists among numerous peaks, and the remaining peaks are referred to as local peaks (LPs). From the observation of output P-V characteristics,

the possible local peaks within each PV array connection are known.

Efficiency

The efficiency of a PV system is defined as the ratio of maximum power output to the input solar power and is calculated by using Eq. 14

$$\text{Efficiency}(\eta) = \frac{\text{Power at GMPP}}{P_{in}} \quad (14)$$

where P_{in} is solar irradiance falls on the PV array.

Results and Discussions

In this article, eight different 5×4 PV array interconnections are considered, such as SP, TCT, BL, HC, SP-TCT, BL-TCT, HC-TCT, and HC-BL, to investigate the performance under internal and external mismatch effects. Six case studies relating to both internal and external mismatch situations are taken into consideration. In each case, the GMPP, V_{GMPP} , V_{TH} , PL, FF, η , and PLP parameters are obtained and compared for PV array interconnections.

Fig. 7 Case study- E_3 for external mismatch effects

Fig. 8 First two strings with non-identical parameters

External Mismatch Effects or PSCs

Investigation of PV array connections under case study-E1

The P–V characteristics of PV array connections for shading cases I–V in case study- E_1 are shown in Figs. 9, 10 and 11. In shading case-I, multiple peaks are observed on the P–V curve, as shown in Fig. 9a. It is noticed from the figure that the local peaks of all interconnections are very near to the global peaks. In shading case-I, the SP and BL-TCT PV arrays produced true GMPP, which can be observed in Table 3. The P–V characteristics of array interconnections for shading case-II, as shown in Fig. 9b. It is noted from the figure that the local peaks of array connections are far from the global peaks. Whereas, in this case, the TCT and HC-TCT PV arrays produced true GMPP showed in Table 3. Figure 10a and b shows the output P–V characteristics for shading case-III and case-IV. In case-III, multiple peaks

are noted on the P–V curve. It is indicated from the figure that the local peaks are far from the global peaks. In this case, TCT, BL-TCT, and SP-TCT PV arrays produced true GMPP. In case-IV, the location of local peaks is far from the global peaks, as shown in Fig. 10b. In this case, the TCT, BL, and HC-BL PV arrays produced true GMPP. The P–V characteristics of array connections for shading case-V, as shown in Fig. 11. In this case, PV arrays produced equal GMPP listed in Table 3.

From case study- E_1 , it is observed that if the shading effect increased, then the GMPP of all array interconnections decreased for shading cases I–V. Under this study, the obtained parameters such as GMPP, V_{GMPP} , and V_{TH} are presented in Table 3. Also, the other parameters such as PL, FF, η , and PLP are given in Table 4. It is found from the table that the TCT PV array produced the highest GMPP as compared to the other connections under most shading cases.

Investigation of PV array interconnections under case study-E2

The P–V characteristics of PV array connections for shading cases I–V in case study- E_2 are shown in Figs. 12, 13 and 14. In case-I, multiple peaks are observed on the P–V curve. It is noted from the figure that the local peaks are far from the global peaks, as shown in Fig. 12a. Whereas, in this case, the TCT and HC-TCT PV arrays produced true GMPP, which can be observed in Table 5. The P–V characteristics of array interconnections for shading case-II, as shown in Fig. 12b. From the figure, it is noted that the local peaks are far from the global peaks. For this case, the TCT and HC-TCT PV arrays produced true GMPP listed in Table 5. The P–V characteristics for shading case-III and case-IV are shown in Fig. 13a and b respectively. Multiple peaks are noted on the P–V curve for shading case-III, as shown in Fig. 13a. From the figure, it is noticed that the local peaks

Fig. 9 PV array characteristics for case study- E_1

Fig. 10 PV array characteristics for case study- E_1

are far from the global peaks. In this case, the TCT and HC-TCT PV arrays produced true GMPP. In case-IV, the local peaks are far from the global peaks, which can be seen in Fig. 13b. In this case, the PV arrays produced equal GMPP listed in Table 5. In case-V, multiple peaks are observed on the P-V curve, as shown in Fig. 14. The location of local peaks is far from global peaks in this shading case. The GMPP of PV array connections is identical in this case.

From case study- E_2 , it is noted that if the shading effect increased, then the GMPP of all array interconnections decreased for shading cases I–V. Under this case study, the obtained parameters such as GMPP, V_{GMPP} and V_{TH} are presented in Table 5. Also, the other parameters such as PL, FF, η , and PLP are given in Table 6. It is found from the table that the TCT/HC-TCT PV array produced the highest GMPP as compared to the other connections under all shading cases.

Fig. 11 P-V characteristics for case-V in case study- E_1

Investigation of PV array interconnections under case study- E_3

The P-V characteristics of PV array interconnections for shading cases I–V in case study- E_3 are shown in Figs. 15, 16 and 17a. For shading case-I, various multiple peaks are noted on the P-V curve, as shown in Fig. 15a. From the figure, it is found that the local peaks are far from the global peaks. Whereas, in this case, the TCT and HC-TCT PV arrays produced true GMPP listed in Table 7. The P-V characteristics of array interconnections for shading case-II, as shown in Fig. 15b. It is noted from the figure that the local peaks are far from the global peaks. In this case, the TCT PV array is produced true GMPP. Figure 16a and b depicts the P-V characteristics for shading case-III and case-IV, respectively. Figure 16a shows that multiple peaks exist on the P-V curve for shading case-III. It is noted from the figure that the location of local peaks is at a distance from the global peaks. In this case, the TCT PV array produced true GMPP. In case-IV, the conventional and hybrid PV array connections are displayed various peaks on the P-V curve. Among all, the TCT PV array is produced true GMPP is listed in Table 7. Similarly, for case-V, the P-V curve indicates multiple peaks, as shown in Fig. 17a. In this case, the TCT, BL-TCT, and HC-TCT PV arrays produced real GMPP, which can be observed in Table 7.

From case study- E_3 , it is noted that if the shading effect increased, then the GMPP of all array interconnections decreased for shading cases I–V. Under this case study, the obtained parameters such as GMPP, V_{GMPP} and V_{TH} are presented in Table 7. Also, the other parameters such as PL, FF, η , and PLP are given in Table 8. It is found from the table that the TCT PV array produced the highest GMPP as compared to the other interconnections under all shading cases.

Table 3 GMPP, V_{GMPP} and V_{TH} for array interconnections in case study- E_1 under external effects

Configurations	CASE I			CASE II			CASE III			CASE IV			CASE V			Uniform		
	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)
SP	2735	145	5.01	2450	181	1.89	2470	181	1.78	2475	181	1.72	2400	181	1.32	3401	178	9.65
TCT	2687	141	4.89	2580	185	2.15	2508	184	1.98	2480	184	1.85	2400	182	1.32	3401	178	9.65
BL	2687	140	4.81	2520	182	2.08	2485	183	1.92	2480	183	1.72	2400	179	1.32	3401	178	9.65
HC	2730	145	5.01	2500	184	2.01	2500	182	1.92	2475	183	1.72	2400	179	1.32	3401	178	9.65
SP-TCT	2690	141	4.12	2500	180	2.01	2508	182	1.92	2475	183	1.72	2400	179	1.32	3401	178	9.65
BL-TCT	2735	145	5.01	2512	181	2.10	2508	183	1.92	2475	182	1.72	2400	180	1.32	3401	178	9.65
HC-TCT	2730	145	5.00	2580	182	2.15	2500	182	1.89	2475	183	1.72	2400	181	1.32	3401	178	9.65
HC-BL	2690	140	4.98	2510	183	2.12	2500	183	1.89	2480	184	1.75	2400	181	1.32	3401	178	9.65

The significance of bold is to high the value of the parameters

Table 4 PL, FF, η and PLP for array interconnections in case study- E_1 under external effects

Configurations	CASE I				CASE II				CASE III				CASE IV				CASE V				Uniform			
	PLoss	FF	η	PLP	PLoss	FF	η	PLP	PLoss	FF	η	PLP	PLoss	FF	η	PLP	PLoss	FF	η	PLP	PLoss	FF	η	PLP
SP	665	0.59	10.69	1	950	0.53	9.57	1	930	0.53	9.65	1	925	0.538	9.67	1	1000	0.526	9.38	0	0	0.739	13.3	0
TCT	713	0.58	10.59	1	820	0.56	10.08	1	892	0.545	9.80	1	920	0.539	9.69	1	1000	0.526	9.38	0	0	0.739	13.3	0
BL	713	0.58	10.5	1	880	0.54	9.85	1	915	0.540	9.71	1	920	0.539	9.69	1	1000	0.526	9.38	0	0	0.739	13.3	0
HC	670	0.59	10.6	1	900	0.53	9.77	1	900	0.543	9.77	1	925	0.538	9.69	1	1000	0.526	9.38	0	0	0.739	13.3	0
SP-TCT	710	0.58	10.5	1	900	0.532	9.77	1	892	0.545	9.80	1	925	0.538	9.67	1	1000	0.526	9.38	0	0	0.739	13.3	0
BL-TCT	665	0.59	10.69	1	888	0.54	9.82	1	892	0.545	9.80	1	925	0.538	9.67	1	1000	0.526	9.38	0	0	0.739	13.3	0
HC-TCT	670	0.58	10.67	1	820	0.56	10.08	1	900	0.543	9.77	1	925	0.538	9.67	1	1000	0.526	9.38	0	0	0.739	13.3	0
HC-BL	710	0.59	10.51	1	888	0.54	9.82	1	900	0.54	9.77	1	920	0.539	9.69	1	1000	0.526	9.38	0	0	0.739	13.3	0

Fig. 12 PV array characteristics for case study- E_2

Internal Mismatch Effects

Investigation of PV array interconnections under case study-I1

Case study- I_1 is divided into five sub-cases I-V. In each case, the R_S of PV modules increased to 15% of its actual value in the first two strings of the PV arrays (refer in Fig. 8). In case-I, the R_S is increased to 15% of its actual value, i.e., 0.52 to 0.59 in the PV arrays. In this case, the TCT array is produced real maximum power is listed in Table 9. In case-II, the R_S is increased to 30% of its actual value, i.e., 0.52 to 0.67 in the PV arrays. For this case, the TCT and HC-BL PV arrays produced real maximum power is showed in Table 9. In case-III & IV, the R_S is increased to 45% & 60% of its actual values, respectively. The generated real maximum powers of case-III & case-IV are given in Table 9. In case-V, the R_S is increased to 75% of its actual value, i.e., 0.52 to 0.92 in the PV arrays. In this case, the TCT array is produced real maximum power, which can be observed in Table 9.

From case study- I_1 , it is noted that increasing the series resistance of the PV modules decreased the maximum power production and voltage of the array interconnections. Under this study, the obtained parameters such as GMPP, V_{GMPP} and V_{TH} are presented in Table 9. Also, the other parameters such as PL, FF, η , and PLP are given in Table 10. It is found from the table that the TCT array is produced the highest maximum power as compared to the other interconnections in most cases.

Investigation of PV array interconnections under case study-I2

Case study- I_2 is divided into five sub-cases I-V. In each case, the R_P of PV modules decreased to 15% of its actual value in the first two strings of the PV arrays (refer in Fig. 8). In case-I, the R_P is decreased to 15% of its actual value, i.e., 162.2 to 137.8 in the PV arrays. In this case, the TCT and HC-BL PV arrays produced real maximum power is listed in Table 11. In case-II, the R_P is decreased to 30% of its actual value, i.e.,

Fig. 13 PV array characteristics for case study- E_2

Fig. 14 P-V characteristics for case-V in case study- E_2

162.2 to 113.5 in the PV arrays. In this case, the TCT and HC PV arrays produced real maximum power. In case-III & IV, the R_P is decreased to 45% & 60% of its actual values, respectively. The generated real maximum powers of case-III & case-IV are given in Table 11. In case-V, the R_P is decreased to 75% of its actual value, i.e., 162.2 to 50.5 in the PV arrays. For this case, the TCT array is produced real maximum power is given in Table 11.

From case study- I_2 , it is noted that decreasing the shunt resistance of the PV modules decreased the maximum power production and voltage of the array interconnections. Under this case study, the obtained parameters such as GMPP, V_{GMPP} and V_{TH} are presented in Table 11. Also, the other parameters such as PL, FF, η , and PLP are given in Table 12. It is found from the table that the TCT and HC PV arrays produced the highest GMPP as compared to the other interconnections in most cases.

Investigation of PV array interconnections under case study-I3

Case study- I_3 is divided into five sub-cases I-V. In each case, the ideality factor (a) of PV modules decreased to 15% of its actual value in the first two strings of PV array interconnections (refer in Fig. 8). In case-I, the n is decreased to 15% of its actual value, i.e., 0.96 to 0.81 in the PV arrays. In this case, the TCT and HC-BL PV arrays produced real maximum power listed in Table 13. In case-II, the n is decreased to 30% of its actual value, i.e., 0.96 to 0.67 in the PV arrays. In this case, the TCT and HC PV arrays produced real maximum power. In case-III & IV, the n is decreased to 45% & 60% of its actual values, respectively. The generated real maximum powers of case-III & case-IV are given in Table 11. In case-V, the n is decreased to 75% of its actual value, i.e., 0.96 to 0.25 in the PV arrays. In this case, the real maximum power produced by the TCT array.

Table 5 GMPP, V_{GMPP} and V_{TH} for array interconnections in case study- E_2 under external effects

interconnections	CASE I			CASE II			CASE III			CASE IV			CASE V			Uniform		
	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)
SP	2920	170	5.02	2450	171	3.98	2020	107	2.01	2005	105	1.42	1490	175	-3.65	3401	176	9.65
TCT	3020	176	5.10	2580	175	4.12	2050	178	2.08	2005	108	1.42	1490	178	-3.65	3401	176	9.65
BL	2960	173	5.05	2520	172	4.05	2009	108	2.02	2005	104	1.42	1490	173	-3.65	3401	176	9.65
HC	2920	171	5.02	2500	174	4.02	2018	104	2.01	2005	102	1.42	1490	175	-3.65	3401	176	9.65
SP-TCT	3000	175	5.07	2500	173	4.02	2010	103	2.0	2005	103	1.42	1490	176	-3.65	3401	176	9.65
BL-TCT	3000	176	5.07	2510	172	4.08	2009	102	2.0	2005	101	1.42	1490	178	-3.65	3401	176	9.65
HC-TCT	3020	176	5.10	2580	174	4.12	2050	177	2.08	2005	102	1.42	1490	175	-3.65	3401	176	9.65
HC-BL	2960	177	5.05	2510	173	4.09	2020	103	2.01	2005	105	1.42	1490	172	-3.65	3401	176	9.65

The significance of bold is to high the value of the parameters

Table 6 PL, FF, η and PLP for array interconnections in case study- E_2 under external effects

inter con- nections	CASE I				CASE II				CASE III				CASE IV				CASE V				uniform			
	P.Loss	FF	η	PLP	P.Loss	FF	η	PLP	P.Loss	FF	η	PLP	P.Loss	FF	η	PLP	P.Loss	FF	η	PLP	P.Loss	FF	η	PLP
SP	480	0.635	11.41	1	950	0.533	9.57	1	1380	0.439	7.89	1	1395	0.43	7.83	1	1910	0.32	5.82	1	0	0.739	13.3	0
TCT	380	0.657	11.80	1	820	0.56	10.08	1	1350	0.446	8.01	1	1395	0.436	7.83	1	1910	0.32	5.82	1	0	0.739	13.3	0
BL	440	0.644	11.57	1	880	0.54	9.85	1	1391	0.437	7.85	1	1395	0.436	7.83	1	1910	0.32	5.82	1	0	0.739	13.3	0
HC	480	0.635	11.41	1	900	0.543	9.77	1	1382	0.44	7.88	1	1395	0.436	7.83	1	1910	0.32	5.82	1	0	0.739	13.3	0
SP-TCT	400	0.652	11.7	1	900	0.543	9.77	1	1390	0.43	7.85	1	1395	0.43	7.83	1	1910	0.32	5.82	1	0	0.739	13.3	0
BL-TCT	400	0.65	11.7	1	890	0.546	9.82	1	1391	0.437	7.85	1	1395	0.436	7.83	1	1910	0.32	5.82	1	0	0.739	13.3	0
HC-TCT	380	0.657	11.7	1	820	0.56	10.08	1	1350	0.446	8.01	1	1395	0.43	7.83	1	1910	0.32	5.82	1	0	0.739	13.3	0
HC-BL	440	0.64	11.57	1	890	0.54	9.82	1	1380	0.439	7.89	1	1395	0.43	7.83	1	1910	0.32	5.82	1	0	0.739	13.3	0

Fig. 15 PV array characteristics for case study- E_3

Fig. 16 PV array characteristics for case study- E_3

Fig. 17 PV array characteristics for case-V in case study- E_3 and uniform condition

Table 7 GMPP, V_{GMPP} and V_{TH} for array interconnections in shading case- E_3 under external effects

Configurations	CASE I			CASE II			CASE III			CASE IV			CASE V			Uniform		
	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)
SP	2920	171	5.02	2470	168	4.18	1960	170	1.09	1500	180	-6.3	2610	144	3.36	3401	176	9.65
TCT	3020	176	5.10	2600	173	4.91	2100	178	1.56	2470	172	-3.2	2985	168	3.86	3401	176	9.65
BL	2960	173	5.05	2500	170	4.23	2020	172	1.12	1980	177	-4.1	2610	143	3.68	3401	176	9.65
HC	2920	173	5.02	2500	170	4.23	1980	174	1.01	1980	176	-4.0	2500	176	3.21	3401	176	9.65
SP-TCT	3000	175	5.07	2506	173	4.31	2035	173	1.11	1980	147	-4.1	2485	148	3.18	3401	176	9.65
BL-TCT	3000	176	5.07	2500	171	4.31	1985	172	1.06	1980	147	-4.0	2985	167	3.28	3401	176	9.65
HC-TCT	3020	176	5.10	2470	170	4.21	1920	171	1.05	2010	177	-3.8	2985	167	3.88	3401	176	9.65
HC-BL	2960	177	5.05	2500	173	4.21	1996	173	1.03	2000	176	-3.8	2505	176	3.38	3401	176	9.65

The significance of bold is to high the value of the parameters

Table 8 PL, FF, η and PLP for array interconnections in case study- E_3 under external effects

Configurations	CASE I				CASE II				CASE III				CASE IV				CASE V				uniform			
	PLoss	FF	η	PLP	PLoss	FF	η	PLP	PLoss	FF	η	PLP	PLoss	FF	η	PLP	PLoss	FF	η	PLP	PLLoss	FF	η	PLP
SP	480	0.63	11.41	1	930	0.537	9.65	1	1440	0.426	7.66	1	1900	0.32	5.86	2	790	0.56	10.20	1	0	0.739	13.3	0
TCT	380	0.657	11.80	1	800	0.56	10.16	1	1300	0.45	8.20	2	940	0.53	9.65	0	415	0.65	11.6	1	0	0.739	13.3	0
BL	440	0.644	11.87	1	900	0.543	9.77	1	1380	0.439	7.89	2	1420	0.430	7.74	2	790	0.56	10.2	1	0	0.739	13.3	0
HC	480	0.635	11.41	1	900	0.54	9.77	2	1420	0.43	7.74	2	1420	0.430	7.74	2	900	0.54	9.77	2	0	0.739	13.3	0
SP-TCT	400	0.652	11.72	1	894	0.545	9.79	1	1365	0.44	7.95	2	1420	0.430	7.74	2	915	0.54	9.71	2	0	0.739	13.3	0
BL-TCT	400	0.65	11.72	1	900	0.54	9.77	2	1415	0.431	7.75	2	1420	0.430	7.74	2	415	0.65	11.61	1	0	0.739	13.3	0
HC-TCT	380	0.657	11.72	1	930	0.537	9.61	2	1480	0.41	7.50	2	1390	0.437	7.85	2	415	0.65	11.6	1	0	0.739	13.3	0
HC-BL	440	0.64	11.57	1	900	0.54	9.77	2	1404	0.43	7.80	2	1400	0.435	7.81	2	895	0.545	9.79	2	0	0.739	13.3	0

Table 9 GMPP, V_{GMPP} and V_{TH} for array interconnections in case study- I_1 under internal effects

Configurations	CASE I			CASE II			CASE III			CASE IV			CASE V			uniform		
	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)
SP	2662	168	1.85	2380	161	0.41	2150	155	-0.33	1950	150	-0.44	1850	147	-0.65	3401	178	9.65
TCT	2873	167	1.98	2440	161	0.43	2298	154	0.23	2190	151	0.35	2009	148	-0.55	3401	178	9.65
BL	2650	164	1.83	2350	162	0.41	2199	153	-0.33	2090	149	-0.42	1910	148	-0.65	3401	178	9.65
HC	2662	165	1.82	2380	161	0.42	2218	154	-0.33	2085	150	-0.42	1890	148	0.65	3401	178	9.65
SP-TCT	2570	165	1.82	2390	161	0.43	2210	152	-0.33	1985	150	-0.32	1902	147	-0.65	3401	178	9.65
BL-TCT	2660	165	1.88	2310	162	0.42	2230	151	-0.31	2052	149	-0.42	1895	145	-0.65	3401	178	9.65
HC-TCT	2667	165	1.86	2360	162	0.42	2221	152	-0.33	2298	149	-0.42	1910	145	-0.65	3401	178	9.65
HC-BL	2766	165	1.85	2440	160	0.41	2238	153	-0.33	2190	149	-0.43	1912	148	-0.65	3401	178	9.65

The significance of bold is to high the value of the parameters

Table 10 PL, FF, η and PLP for array interconnections in case study- I_1 under internal effects

Configurations	CASE I				CASE II				CASE III				CASE IV				CASE V				uniform			
	PL	FF	η	PLP	PL	FF	η	PLP	PL	FF	η	PLP	PL	FF	η	PLP	PL	FF	η	PL	PL	FF	η	PLP
SP	949	0.55	9.9	0	1231	0.49	9.37	0	1281	0.50	9.4	0	1320	0.49	9.37	0	1400	0.46	8.9	0	0	0.739	13.3	0
TCT	916	0.57	10.1	0	1100	0.52	10.01	0	1195	0.525	9.60	0	1150	0.5	9.49	0	1280	0.48	9.01	0	0	0.739	13.3	0
BL	922	0.54	9.91	0	1132	0.51	9.65	0	1160	0.510	9.41	0	1250	0.489	9.19	0	1390	0.45	8.99	0	0	0.739	13.3	0
HC	923	0.54	10.0	0	1190	0.51	9.57	0	1290	0.5	9.67	0	1260	0.48	9.19	0	1380	0.55	8.91	0	0	0.739	13.3	0
SP-TCT	922	0.55	10.01	0	1110	0.52	9.57	0	1150	0.515	9.70	0	1242	0.48	9.27	0	1390	0.45	8.91	0	0	0.739	13.3	0
BL-TCT	935	0.52	9.9	0	1060	0.52	9.52	0	1190	0.515	9.70	0	1260	0.47	9.27	0	1380	0.45	8.9	0	0	0.739	13.3	0
HC-TCT	932	0.53	9.89	0	1190	0.52	10.01	0	1380	0.513	9.67	0	1260	0.48	9.37	0	1370	0.456	8.9	0	0	0.739	13.3	0
HC-BL	916	0.53	10.01	0	1140	0.52	9.52	0	1350	0.51	9.67	0	1270	0.5	9.49	0	1375	0.45	8.9	0	0	0.739	13.3	0

Table 11 GMPP, V_{GMPP} and V_{TH} for array interconnections in case study- I_2 under internal effects

Configurations	CASE I			CASE II			CASE III			CASE IV			CASE V			Uniform		
	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)
SP	2762	132	1.75	2590	165	-0.41	2350	157	-0.663	2109	160	-0.32	1950	171	0.61	3401	178	9.65
TCT	2973	134	1.88	2675	161	0.25	2498	155	0.83	2190	171	0.85	2009	172	0.62	3401	178	9.65
BL	2750	126	1.78	2550	167	-0.42	2356	168	-0.663	2105	174	-0.32	1930	169	0.55	3401	178	9.65
HC	2762	129	1.75	2675	171	-0.42	2498	168	-0.663	2156	173	-0.32	1942	171	0.59	3401	178	9.65
SP-TCT	2770	131	1.75	2648	168	-0.42	2350	169	-0.663	2105	163	-0.32	1952	167	0.59	3401	178	9.65
BL-TCT	2860	131	1.75	2620	169	-0.41	2362	169	-0.663	2143	162	-0.32	1985	161	0.55	3401	178	9.65
HC-TCT	2867	129	1.75	2660	169	-0.40	2380	172	-0.663	2168	173	-0.32	1995	171	0.55	3401	178	9.65
HC-BL	2973	130	1.75	2690	170	-0.40	2367	163	-0.663	2190	174	-0.32	1982	168	0.59	3401	178	9.65

The significance of bold is to high the value of the parameters

Table 12 PL, FF, η and PLP PV array interconnections in case study- I_2 under internal effects

Configurations	CASE I				CASE II				CASE III				CASE IV				CASE V				Uniform			
	PL	FF	η	PLP	PL	FF	η	PLP	PL	FF	η	PLP	PL	FF	η	PLP	PL	FF	η	PL	PLP	FF	η	PLP
SP	969	0.53	9.91	0	1241	0.49	9.87	0	1281	0.49	9.4	0	1310	0.49	9.31	0	1400	0.46	8.9	0	0	0.739	13.3	0
TCT	926	0.56	10.11	0	1120	0.52	9.95	0	1175	0.525	9.60	0	1190	0.5	9.5	0	1280	0.48	9.01	0	0	0.739	13.3	0
BL	962	0.55	9.92	0	1122	0.54	9.89	0	1180	0.50	9.41	0	1250	0.489	9.19	0	1390	0.45	8.99	0	0	0.739	13.3	0
HC	961	0.55	10.01	0	1130	0.52	9.87	0	1230	0.5	9.67	0	1260	0.48	9.29	0	1390	0.55	8.91	0	0	0.739	13.3	0
SP-TCT	965	0.55	10.02	0	1140	0.523	9.87	0	1140	0.502	9.70	0	1242	0.48	9.27	0	1390	0.45	8.91	0	0	0.739	13.3	0
BL-TCT	955	0.54	9.9	0	1050	0.523	9.82	0	1160	0.505	9.70	0	1260	0.47	9.27	0	1380	0.45	8.9	0	0	0.739	13.3	0
HC-TCT	942	0.54	9.90	0	1140	0.523	9.9	0	1280	0.503	9.67	0	1260	0.48	9.37	0	1360	0.456	8.9	0	0	0.739	13.3	0
HC-BL	946	0.54	10.02	0	1120	0.523	9.82	0	1250	0.50	9.67	0	1270	0.48	9.49	0	1365	0.45	8.9	0	0	0.739	13.3	0

Table 13 GMPP, V_{GMPP} and V_{TH} for array configurations in case study- I_3 under internal effects

Configurations	CASE I			CASE II			CASE III			CASE IV			CASE V			Uniform		
	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)	GMPP (W)	V_{GMPP} (V)	V_{TH} (V)
SP	3204	163	1.45	2880	158	-0.33	2650	148	-0.59	2450	141	-0.21	2250	134	0.65	3401	178	9.65
TCT	3298	169	1.58	2940	161	-0.31	2798	151	0.63	2590	143	0.65	2309	137	0.65	3401	178	9.65
BL	3201	166	1.45	2845	158	-0.33	2630	146	-0.53	2490	141	-0.22	2260	135	0.65	3401	178	9.65
HC	3201	162	1.42	2940	159	-0.33	2618	146	-0.54	2485	143	-0.22	2260	134	0.65	3401	178	9.65
SP-TCT	3200	161	1.42	2870	156	-0.33	2610	145	-0.56	2385	139	-0.22	2275	133	0.65	3401	178	9.65
BL-TCT	3250	161	1.42	2810	157	-0.32	2630	145	-0.56	2452	139	-0.22	2286	133	0.65	3401	178	9.65
HC-TCT	3277	159	1.42	2890	159	-0.32	2621	142	-0.53	2468	141	-0.22	2305	131	0.65	3401	178	9.65
HC-BL	3298	160	1.41	2890	160	-0.32	2798	151	-0.53	2490	141	-0.22	2300	131	0.65	3401	178	9.65

The significance of bold is to high the value of the parameters

From case study- I_3 , it is noted that decreasing the ideality factor of the PV modules reduced the maximum power production and voltage of the array interconnections. Under this case, the obtained parameters such as GMPP, V_{GMPP} and V_{TH} are presented in Table 13. Also, the other parameters such as PL, FF, η , and PLP are given in Table 14. It is found from the table that the TCT PV array is produced the highest GMPP as compared to the other interconnections in most cases.

Under all mismatch cases, the obtained parameters such as GMPP, V_{GMPP} , V_{TH} , PL, FF, η and PLP of PV array connections are compared with the uniform condition (refer in Tables 3–14). In uniform condition, only one maximum power point (MPP) exist in P-V characteristics, as shown in Fig. 17(b). The figure (refer in Fig. 17b) shows that PV arrays produced equal MPP with respect to the maximum voltage of 176 V. The other evaluated parameters in uniform conditions such as PL, FF, η , and PLP are listed in Tables 3–14.

Energy Yields for PV Array Interconnections

In the PV array, the shading effect occupies a smaller area. As a consequence, the shaded area does not allow the current flow between PV modules. The shaded module consumes the power rather than production. Under this situation, the solar PV array's power is much less than the designed one. One of the approaches to overcome this difficulty is the PV modules interconnection that allows the current flow in the PV array under PSCs. Various types of connections for the PV array are available in the literature, such as series-parallel, total-cross-tied, bridge-link, honey-comb, SP-TCT, and BL-TCT. The most challenging aspect of constructing array interconnections is selecting the size of the PV modules and cables.

In this section, a simple calculation is performed to estimate the revenue from energy savings of PV array connections for 3.4 kW (i.e., 5×4 array) solar plant under PSCs. The shading condition is given in Fig. 5. Each shading case can stay up to 10 minutes in 1 sun hour. The 5×4 array consists of 20 PV modules connected in different styles, as mentioned above. Each module generates 170 W peak power at STC. The short circuit current (I_{sc}) of each module is 5.2 A, and hence the wire used for connecting the modules in series in each column must have an ampacity of 1.56 times I_{sc} (i.e., 7.8 A), as per the National Electric Code [35]. Hence, 20 AWG wires, which have an ampacity of 8.1 A in the enclosed condition. The various cost components of the system that have been taken into account are: PV modules (\$11,480), wiring (\$580), and monitoring system (\$10,900). Table 15 shows income generation calculations for each PV array at the tariff Rs.15 per unit cost. In addition

Table 14 PL, FF, η and PLP for array interconnections in case study- I_3 under internal effects

Configu rations	CASE I					CASE II					CASE III					CASE IV					CASE V					uniform						
	P _{Loss}	FF	η	PLP	P _{Loss}	FF	η	PLP	P _{Loss}	FF	η	PLP	P _{Loss}	FF	η	PLP	P _{Loss}	FF	η	PLP	P _{Loss}	FF	η	PLP	P _{Loss}	FF	η	PLP	P _{Loss}	FF	η	
SP	939	0.52	9.9	0	1261	0.48	9.19	0	1231	0.502	9.5	0	1230	0.51	9.32	0	1201	0.502	9.17	0	0	0.739	13.3	0	0	0.739	13.3	0	0	0.739	13.3	0
TCT	918	0.56	10.1	0	1095	0.51	10.02	0	1067	0.53	9.71	0	1190	0.53	9.49	0	1120	0.538	9.21	0	0	0.739	13.3	0	0	0.739	13.3	0	0	0.739	13.3	0
BL	932	0.54	9.90	0	1165	0.51	9.65	0	1160	0.510	9.41	0	1180	0.52	9.19	0	1190	0.521	9.19	0	0	0.739	13.3	0	0	0.739	13.3	0	0	0.739	13.3	0
HC	928	0.51	10.01	0	1201	0.50	9.56	0	1190	0.52	9.68	0	1175	0.518	9.29	0	1180	0.52	9.16	0	0	0.739	13.3	0	0	0.739	13.3	0	0	0.739	13.3	0
SP-TCT	922	0.55	10.00	0	1210	0.53	9.55	0	1190	0.518	9.70	0	1132	0.518	9.27	0	1170	0.53	9.18	0	0	0.739	13.3	0	0	0.739	13.3	0	0	0.739	13.3	0
BL-TCT	925	0.528	9.9	0	1170	0.52	9.52	0	1162	0.515	9.70	0	1140	0.518	9.29	0	1170	0.52	9.17	0	0	0.739	13.3	0	0	0.739	13.3	0	0	0.739	13.3	0
HC-TCT	938	0.52	9.82	0	1150	0.51	10.01	0	1150	0.513	9.67	0	1140	0.515	9.37	0	1160	0.512	9.11	0	0	0.739	13.3	0	0	0.739	13.3	0	0	0.739	13.3	0
HC-BL	926	0.51	9.98	0	1140	0.52	9.56	0	1120	0.52	9.69	0	1140	0.517	9.36	0	1165	0.516	9.12	0	0	0.739	13.3	0	0	0.739	13.3	0	0	0.739	13.3	0

to this, the estimated parameters are graphically represented in Fig. 18.

Table 15 shows that the TCT array is generated the highest energy with improved income as compared to the other array interconnections. Also, the proposed HC-TCT and HC-BL arrays delivered more income(\$) equal to the TCT and far from the other interconnections.

Discussions

This article examines the performance of eight PV array interconnections under both internal and external mismatch effects. Six case studies relating to internal and external mismatch situations are taken into account to analyse power production's impact. For the internal mismatch study, the internal parameters of the PV modules, such as R_s , R_p and n , are varied. The PV modules are subjected to partially shaded in a row, column, and diagonal wise in the external investigation.

The study revealed that the variations in internal parameters (i.e., majorly R_s) affect the PV arrays' output power. These variations are listed in Tables 9–14. The obtained results concluded that the TCT array shows better performance compared to other interconnections. Besides, the proposed connections (HC-BL and HC-TCT) produced the highest maximum power and fill-factor, which nearer to the TCT array and far from the other array interconnections. In the external case, row shading resulted in a higher power output reduction than those for other shading conditions (refer in Tables 3–8). Compared with other interconnections, the TCT array is provided better results. Also, the proposed HC-BL and HC-TCT PV arrays performance comparable to TCT under most shading cases.

Merits of Proposed Hybrid PV Array Interconnections

Among the conventional and hybrid connections, the TCT array is exhibited superior performance under both mismatch situations. The drawback of the TCT array is that if one or more PV modules are shaded or malfunctioned in a row, the PV array's overall current decreases. Also, the TCT array installation is time-consuming and required additional wiring than SP, BL, and HC array interconnections. In this paper, hybrid interconnections are suggested to solve these problems. The advantage of the proposed connections is that the current can flow in the PV array with the tie-lines provided between modules, even if shading occurs. The performance of the proposed interconnections is relatively similar to the TCT array and higher than those of other conventional and hybrid interconnections under internal and external mismatch effects. The proposed

Table 15 Obtained revenue generation from energy savings under case study- E_1

Shadings & Index	SP	TCT	BL	HC	SP-TCT	BL-TCT	HC-TCT	HC-BL
case-I	2735 W	2687 W	2687 W	2730 W	2690 W	2700 W	2730 W	2700 W
case-II	2450 W	2580 W	2580 W	2500 W	2500 W	2512 W	2580 W	2530 W
case-III	2470 W	2508 W	2485 W	2500 W	2500 W	2500 W	2508 W	2508 W
case-IV	2475 W	2480 W	2480 W	2471 W	2470 W	2470 W	2475 W	2480 W
case-V	2400 W	2400 W	2400 W	2400 W	2400 W	2400 W	2400 W	2400 W
Total extracted energy per day kW-h	12.8	14.1	13.1	13.2	13.1	12.5	13.5	13.7
Total extracted energy per year kW-h	4672	5146.5	4746.5	4764	4699.5	4672	4918.3	4946.5
Total revenue generated per year Rs.15/kW-h	70080	77197.5	70980	71460	71992.5	69974.5	73992.5	74974.5
Total income in \$ per year	1120.5	1290.2	1220.2	1220.2	1238.6	1120.5	1276.3	1280.2

interconnections required less wiring for installation than the TCT. Moreover, the annual income(\$) generated by the proposed connections comparable with the TCT array and far away from the other array interconnections.

Table 16 shows the power loss comparison between internal and external mismatch effects. The table shows that the external mismatch loss is quite severe than the internal loss on PV arrays. The work presented in this paper is represented in a flow chart, as shown in Fig. 19.

Conclusion

In this paper, the following studies have been reviewed

- The performance of conventional and hybrid PV array connections is analysed under mismatch effects on 5×4 PV arrays by comparing the GMPP, V_{GMPP} , V_{TH} , PL, FF, η and PLP parameters using MATLAB-SIMULINK.

- Two types of mismatch studies are carried out: (i) internal mismatch and (ii) external mismatch. In internal mismatch, the TCT array is reduced the average PL by 9.5% and increased the MPP by 12%, FF by 7.8% compared with those other connections in most cases in the case study- I_1 . Similarly, the TCT array is reduced the average PL by 7% and increased the MPP by 10%, FF by 6.8% for case study- I_2 , and the TCT array is reduced the average PL by 7.6% and increased the MPP by 11%, FF by 6.5% for case study- I_3 .
- In external mismatch, the TCT array is reduced the average PL by 7.5% and increased the GMPP by 10%, FF by 6.8% under most shading cases in the case study- E_1 . Similarly, the TCT array is reduced the average PL by 7% and increased the GMPP by 10.6%, FF by 6.9% for case study- E_2 , and the TCT array is reduced the average PL by 8.1% and increased the GMPP by 12.2%, FF by 7.8% for case study- E_3 .
- The two main observations are made from this study are as follows: (i) TCT PV array is enhanced the overall performance under both internal and external

Fig. 18 Estimated energy indices for array interconnections**Table 16** Calculated power loss under internal and external mismatch effects

PV arrays	Average power loss(%)	
	Internal mismatch effects	External mismatch effects
SP	19.2%	22.2%
TCT	16.8%	17.2%
BL	18.1%	21.9%
HC	18.6%	21.7%
SP-TCT	17.9%	22.1%
BL-TCT	18.8%	21.5%
HC-TCT	17.1%	18.8%
HC-BL	16.2%	18.1%

Fig. 19 Flowchart of this study

mismatch effects. (ii) The proposed HC–TCT and HC–BL PV arrays also showed superior performance in both mismatch effects.

Financial and Ethical disclosures

Funding There is no funding for this paper.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

- Samal S, Hota PK, Barik PK (2020) Performance improvement of a distributed generation system using unified power quality conditioner. *Technol Econ Smart Grids Sustain Energy* 5(1):1–16
- Garniwa I, Herdiansyah H et al (2021) Sustainability index of solar power plants in remote areas in Indonesia. *Technol Econ Smart Grids Sustain Energy* 6(1):1–14
- Sai Krishna G, Moger T (2019) Improved sudoku reconfiguration technique for total-cross-tied pv array to enhance maximum power under partial shading conditions. *Renew Sust Energ Rev* 109:333–348
- Sai Krishna G, Moger T (2019) Reconfiguration strategies for reducing partial shading effects in photovoltaic arrays State of the art. *Sol Energy* 182:429–452
- Kaushika ND, Rai AK (2007) An investigation of mismatch losses in solar photovoltaic cell networks. *Energy* 32(5):755–759
- Belhachat F, Larbes C (2018) A review of global maximum power point tracking techniques of photovoltaic system under partial shading conditions. *Renew Sust Energ Rev* 92:513–553
- Malathy S, Ramaprabha R (2017) Reconfiguration strategies to extract maximum power from photovoltaic array under partially shaded conditions. *Renewable and Sustainable Energy Reviews*
- Bingol O, Ozkaya B (2018) Analysis and comparison of different pv array configurations under partial shading conditions. *Sol Energy* 160:336–343
- Wang Y-J, Hsu P-C (2011) An investigation on partial shading of pv modules with different connection configurations of pv cells. *Energy* 36(5):3069–3078
- Gautam NK, Kaushika ND (2002) Reliability evaluation of solar photovoltaic arrays. *Sol Energy* 72(2):129–141
- Gautam NK, Kaushika ND (2001) Network analysis of fault-tolerant solar photovoltaic arrays. *Sol Energy Mater Sol Cells* 69(1):25–42
- Kaushika ND, Gautam NK (2003) Energy yield simulations of interconnected solar pv arrays. *IEEE Trans Energy Convers* 18(1):127–134
- Belhachat F, Larbes C (2015) Modeling, analysis and comparison of solar photovoltaic array configurations under partial shading conditions. *Sol Energy* 120:399–418
- Shams El-Dein MZ, Kazerani M, Salama MMA (2013) An optimal total cross tied interconnection for reducing mismatch losses in photovoltaic arrays. *IEEE Trans Sustain Energy* 4(1):99–107
- Shams El-Dein MZ, Kazerani M, Salama MMA (2013) Optimal photovoltaic array reconfiguration to reduce partial shading losses. *IEEE Trans Sustain Energy* 4(1):145–153
- Indu Rani B, Saravana Ilango G, Nagamani C (2013) Enhanced power generation from pv array under partial shading conditions by shade dispersion using su do ku configuration. *IEEE Trans Sustain Energy* 4(3):594–601
- Ramaprabha R, Mathur BL (2012) A comprehensive review and analysis of solar photovoltaic array configurations under partial shaded conditions. *International Journal of Photoenergy*
- Dhimish M, Holmes V, Mehrdadi B, Dales M, Chong B, Li Z (2017) Seven indicators variations for multiple pv array configurations under partial shading and faulty pv conditions. *Renew Energy* 113:438–460
- Pendem SR, Mikkili S (2018) Modelling and performance assessment of pv array topologies under partial shading conditions to mitigate the mismatching power losses. *Sol Energy* 160:303–321
- Pendem SR, Mikkili S (2018) Modeling, simulation and performance analysis of solar pv array configurations (series, series-parallel and honey-comb) to extract maximum power under partial shading conditions. *Energy Rep* 4:274–287
- Yadav AS, Pachauri RK, Chauhan YK (2016) Comprehensive investigation of pv arrays with puzzle shade dispersion for improved performance. *Sol Energy* 129:256–285
- Ahmad R, Murtaza AF, Sher HA, Shami UT, Olalekan S (2017) An analytical approach to study partial shading effects on pv array supported by literature. *Renew Sust Energ Rev* 74:721–732

23. Nguyen D, Lehman B (2008) A reconfigurable solar photovoltaic array under shadow conditions, pp 980–986
24. Picault D, Raison B, Bacha S, Aguilera J, de la Dasa J (2010) Changing photovoltaic array interconnections to reduce mismatch losses: a case study, pp 37–40
25. Bidram A, Davoudi A, Balog RS (2012) Control and circuit techniques to mitigate partial shading effects in photovoltaic arrays. *IEEE J Photovolt* 2(4):532–546
26. Bana S, Saini RP (2017) Experimental investigation on power output of different photovoltaic array configurations under uniform and partial shading scenarios. *Energy* 127:438–453
27. Pendem SR, Mikkili S (2018) Modeling, simulation, and performance analysis of pv array configurations (series, series-parallel, bridge-linked, and honey-comb) to harvest maximum power under various partial shading conditions. *Int J Green Energy* 15(13):795–812
28. Satpathy PR, Jena S, Sharma R (2018) Power enhancement from partially shaded modules of solar pv arrays through various interconnections among modules. *Energy* 144:839–850
29. Jha V, Triar US (2019) A detailed comparative analysis of different photovoltaic array configurations under partial shading conditions. *Int Trans Electr Energy Syst*:e12020
30. Wang Y-J, Hsu P-C (2010) Analytical modelling of partial shading and different orientation of photovoltaic modules. *IET Renew Power Gener* 4(3):272–282
31. Gao L, Dougal RA, Liu S, Iotova AP (2009) Parallel-connected solar pv system to address partial and rapidly fluctuating shadow conditions. *IEEE Trans Ind Electron* 56(5):1548–1556
32. Roopa P, Edward Rajan S, Pon Vengatesh R (2011) Performance analysis of pv module connected in various configurations under uniform and non-uniform solar radiation conditions. In: 2011 International conference on Recent advancements in electrical, electronics and control engineering (ICONRAEECE). IEEE, pp 142–149
33. Pon Vengatesh R, Edward Rajan S (2016) Analysis of pv module connected in different configurations under uniform and non-uniform solar radiations. *Int J Green Energy* 13(14):1507–1516
34. Perveen G, Rizwan M, Goel N (2018) Intelligent model for solar energy forecasting and its implementation for solar photovoltaic applications. *J Renew Sustain Energy* 10(6):063702
35. Potnuru SR, Pattabiraman D, Ganesan SI, Chilakapati N (2015) Positioning of pv panels for reduction in line losses and mismatch losses in pv array. *Renew Energy* 78:264–275

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.