Investigation on Effect of Irradiance Change in Maximum Power Extraction From PV Array Interconnection Schemes During Partial Shading Conditions

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ABSTRACT This paper presents the effect of irradiance change in solar photovoltaic (PV) array interconnection schemes under partial shading conditions (PSCs) for optimal selection of PV interconnection schemes in order to extract maximum power (MP) from the PV array. A 4 x 4 PV array is considered to examine the well-known PV interconnection schemes under different shading scenarios at distinct irradiance conditions. Simulation studies and experimental verification are carried out by considering a 30 W PV panel to analyse the performance of the PV array under various dynamic conditions. Comprehensive analysis in terms of fill factor, output power and mismatching power loss is presented by considering different interconnection schemes under various shading scenarios and irradiance levels. From the simulation studies and experimental verification, it is observed that the irradiance magnitude has a significant impact on the PV power generation from array interconnection schemes under PSCs wherein the performance characteristics of the array interconnection schemes vary with the variation in irradiance levels. It is also identified that the irradiance factor needs to be considered as a design variable while selecting the optimal PV array interconnection schemes for maximum power extraction under PSCs.

INDEX TERMS Array interconnection schemes, maximum power extraction, solar photovoltaic, partial shading conditions.

I. INTRODUCTION

A. MOTIVATION

The rapidly diminishing non-renewable sources like oil, natural gas, coal, and other fossil fuels have led to an energy crisis and increased the energy gap between generation and demand [1]. The ever increasing load demand and drastic change in the environmental conditions have compelled the global attention towards renewable energy sources like solar, wind, hydro, geothermal and tidal to find sustainable alternative energy sources. Among these renewable energy sources, solar photovoltaic (PV) is gaining more importance because of its low installation cost, less maintenance, the abundance of sun and ability to install in small and confined places like rooftops [2], [3]. However, the PV panel has its inherent drawbacks like low energy conversion efficiency and dependence on solar irradiance and cell temperature while generating electrical power [4].

Most of the available PV modules in the commercial market have PV cells connected in series to give the desired voltage and current ratings. These PV modules are connected in different array configurations to generate voltage and current ratings as required by the load [5]. In ideal conditions, all the PV modules in an array are receiving uniform irradiance and thus, the non-linear P-V curve of the array has a single maximum power point (MPP) and low complexity...
in MPP tracking [6]. However, due to the sun’s intermittent nature, shadows of the trees and buildings, passing clouds and dust accumulation on PV modules, the PV array receives non-uniform irradiance, which results in reduced power generation and existence of multiple peak points in P-V curve [7]. These conditions are described as partial shading conditions (PSC) and need to be mitigated to generate maximum power from the PV array. For extracting the maximum power under uniform and PSCs, different techniques have been presented in the literature, which include the usage of PV power optimizers (DC-DC/DC-AC converters) [8], MPP tracking (MPPT) algorithms [9]–[11] and different PV interconnection schemes [12], [13]. The PV interconnection schemes are well suited to enhance the PV array performance under all dynamic conditions as they possess low complexity and do not require any extra converters [14]–[16].

Majority of the work done in the literature have concentrated on developing PV array interconnection schemes by considering random irradiance levels during PSCs [16]–[18], and have neglected the effect of irradiance in the selection of optimal PV interconnection schemes for maximum power generation under PSCs. Keeping in view the above-mentioned aspects, this research paper mainly analyzes the effect of irradiance change in maximum power extraction from PV array interconnection schemes during PSCs. A 4×4 PV array is considered and well-known interconnection schemes like series (S), parallel (P), series-parallel (SP), total cross-tied (TCT), bridge link (BL) and honeycomb (HC) with different shading scenarios like row shading, column shading, diagonal shading, centre shading, random shading, and corner shading cases are investigated at an irradiance levels of 100 W/m², 300 W/m², 500 W/m² and 900 W/m² to derive the effect of irradiance in maximum power generation from the array interconnection schemes under PSCs.

B. LITERATURE REVIEW

Over the years, various interconnection schemes have been presented in the literature for generating maximum power from the PV array under PSCs. A comprehensive review on the various static, reconfigurable and metaheuristic PV interconnection schemes are presented by Pachauri et al. [12]. The authors have concluded that TCT scheme has better performance over rest of the interconnection schemes. However, no evidence is presented by considering different PSCs and irradiance effects for the claim made. Patel and Agarwal [13] have presented a generalized method to obtain the P-V and I-V characteristics under PSCs wherein, MATLAB Simulink is used for developing the P-V curves which can be interfaced with other power electronic components for maximum power extraction under PSCs. Villalva et al. [14] have presented a mathematical method for developing PV characteristics under PSCs using open circuit voltage, maximum power value and short circuit current information. A single diode model with equivalent series resistance (ESR) of the power electronic components is considered for studying the PSCs. An investigation on the PSCs with different configuration schemes is presented by Wang and Hsu [15] wherein, an analytical method is used to study the PSCs in a PV module. Here, S, SP, TCT, BL and HC configurations are simulated in a PV cell level. However, no detailed configurations are presented regarding the shading scenarios and PSCs are presented. Ramaprabha and Mathur [16] have presented a comprehensive review on the PV interconnection schemes under PSCs. Here, SP, TCT, BL and HC configurations are analysed for PSCs and it is concluded that HC have better performance and less cross ties compared to TCT scheme. However, the analysis mainly depends on the constant shading conditions and the fixed irradiance levels. An analysis on mismatching power loss under PSC is presented by Moballegh and Jiang [17]. Different interconnection schemes like SP, BL and TCT schemes are examined under PSCs and a power prediction technique is presented to determine the global maximum power under PSCs. However, this analysis considers the fixed irradiance levels in PSCs. A fixed PV interconnection scheme for generating maximum power under PSCs is presented by Rao et al. [18] wherein, a shade dispersion methodology by altering the electrical connections of the PV module in a PV array is presented and compared with TCT, BL and SP methods under different shading scenarios. This analysis does not consider the variation of irradiance under PSCs. Belhachat and Larbes [19] have presented a comprehensive study on S, SP, TCT, BL and HC PV array interconnection schemes under different shading scenarios. A detailed study for 2×2 PV array under shading scenarios like single module shading, row shading, column shading and three module shading is presented and comparison with BL, HC and SP schemes is carried out. It is concluded that under PSCs, the maximum power generation depends strongly on the shading conditions. Mohammadnejad et al. [20] have analyzed TCT PV array under different PSCs. A detailed study for 2×2 PV array under shading scenarios like single module shading, row shading, column shading and three module shading is presented and comparison with BL, HC and SP schemes is carried out.

A simulation study on PV array configurations under various PSCs and faulty conditions is given by Dhimish et al. [22]. Here, S, P, SP, TCT and HC interconnection schemes are analyzed for fixed irradiance PSCs and faulty PV module conditions. This work mainly concentrates on providing information on the performance of different interconnection schemes under different scenarios for optimal selection of PV interconnection schemes. Pendem et al. [23] have presented a detailed modelling, simulation and analysis of S, SP and...
TABLE 1. A summary of the existing works on PV interconnection schemes for maximum power generation under PSCs.

| Author / year | Interconnection schemes | Analysis on PSCs | Analysis on irradiance effect | Remarks |
|---------------|-------------------------|------------------|-------------------------------|---------|
| Y. J. Wang et al. [13]/ 2011 | Static | Not Presented | Not considered | PV cell level interconnection schemes are explored |
| R. Ramprabh et al. [16]/ 2012 | Static | Presented | Not considered | SP, TCT, BL, HC configurations are analyzed |
| S. Moballeg et al. [17]/ 2014 | Static | Presented | Not considered | SP, TCT, BL configurations are analyzed |
| P.S. Rao et al. [18]/ 2014 | Reconfigurable | Presented | A new shade dispersion scheme is presented | |
| F. Belhachat et al. [19]/ 2015 | Static | Presented | Not considered | S, SP, TCT, BL, HC configurations are analyzed |
| S. Mohammadnejad et al. [20]/ 2016 | Static | Presented | Not considered | TCT scheme is explored under PSC |
| P.K. Satpathy et al. [21]/ 2017 | Reconfigurable | Presented | Not considered | A new shade dispersion scheme is presented |
| M. Dhimish et al. [22]/ 2017 | Static | Presented | Not considered | Simulation study on PV interconnection schemes under PSC and faulty conditions is presented |
| S. R. Pendem et al. [23]/ 2018 | Static | Presented | Not considered | S, SP, HC configurations are analyzed |
| M. Amin et al. [24]/ 2017 | Static | Presented | Not considered | S, P, SP configurations are analysed |
| S. R. Pendem et al. [25]/ 2018 | Static | Presented | Not considered | S, P, SP, HC, TCT configurations are analyzed |
| B. Veerasamy et al. [26]/ 2018 | Static | Presented | Not considered | S, SP, HC, TCT configurations are analyzed |
| G. S. Krishna et al. [27]/ 2019 | Reconfigurable | Presented | A new shade dispersion scheme is presented | |
| R. K. Pachauri et al. [21]/ 2020 | Static, reconfigurable and meta heuristic | Not Presented | Not considered | Presented a detailed classification of PV interconnection schemes |
| S. R. Pendem et al. [29]/ 2020 | Static | Presented | Not considered | A module integrated converter based TCT configuration of PV modules is presented |
| P.K. Bonthagorla et al. [28]/ 2021 | Static | Presented | Not considered | Triple tied scheme is presented |
| P.K. Bonthagorla et al. [30]/ 2021 | Static | Presented | Not considered | Mismatching power loss is analyzed in PV configurations |

HC interconnection schemes under PSCs. Here, various PSCs are explored for the performance analysis of the various interconnection schemes. Moreover, this analysis considers random irradiance levels under PSCs. A comparative study on S, SP and TCT configurations is given by Amin et al. [24]. Here, the efficiency of PV interconnection schemes are presented under PSCs. A performance assessment to mitigate mismatching power loss in S, P, SP, TCT, BL and HC scheme is presented by Pendem and Mikkili [25]. Various PSCs are considered and a detailed performance analysis is carried out on reducing the mismatching power loss. However, the irradiance magnitude is randomly considered in the PSCs analysis. Veerasamy et al. [26] have presented a mismatching power loss analysis of S, SP, TCT, BL and HC configurations with fixed irradiance levels at PSCs. Krishna and Moger [27] have presented an electrical reconfiguration strategy for mitigating the PSCs wherein switches are used to disperse the shaded PV modules such that multiple peak points are mitigated. Bonthagarla and Mikkili [28] have presented a triple tied PV array configuration for maximum power generation under PSCs. A comprehensive analysis is presented with conventional interconnection schemes wherein, fixed random irradiance levels are considered for the PSCs analysis. Pendem et al. [29] have presented a module integrated converter based TCT scheme for maximum power extraction from PV array. Here, large number of converters and controllers are used for extracting the maximum power from PV array, which makes it less feasible for practical implementations. An optimal PV array configuration for PSCs is proposed by Bonthagarla and Mikkili [30] wherein, the analysis is presented for reducing cross ties and mismatching power loss. However, the analysis is carried out at a random irradiance levels in PSCs which greatly affects the conclusions drawn.

Therefore, from the detailed literature review presented, it is evident that the effect of irradiance change in selection of PV interconnection schemes is not considered in the existing works and it greatly affects the selection of array interconnection schemes under PSCs. Hence, a detailed analysis needs to be carried out for optimal selection of PV interconnection schemes in PSCs. Table 1 presents the summary of the existing works on PV interconnection schemes for maximum power generation under PSCs.

C. CONTRIBUTIONS & ORGANIZATION OF THE PAPER

The main contributions of this paper are as follows:

1. A detailed investigation on the effect of irradiance change on maximum power generation in PV interconnection schemes under various PSCs is presented.
2. MATLAB based simulation studies and experimental verification of the PV interconnection schemes under different PSCs at various irradiance levels are carried out for realizing the behaviour of PV interconnection schemes under PSCs.
3. Performance of PV interconnection schemes under different PSCs with different irradiance levels are examined to select the optimal PV Interconnection Scheme for maximum power generation under all dynamic operating conditions.
The rest of the paper is organised as follows: section II presents the mathematical modelling of a PV module, while the considered shading scenarios and irradiance levels for analysis are presented in section III. Section IV gives the simulation studies on PV array interconnection schemes under different shading and irradiance levels followed by the experimental verification of the same in section V. In section VI, the performance analysis and comparative study is carried out. Section VII concludes the work followed by references at the end.

II. MODELLING OF PV MODULE

A commercial PV module is an interconnection of PV cells connected in series. The overall power generation from this PV module depends on temperature of PV cell and incident solar irradiance on it. Various mathematical modelling of PV cells are reported in the literature [12], [13] out of which, single diode and two diode models are extensively used. In this work, a single diode model of SPV cell is used for modelling of SPV module, as it is widely accepted in PV cell modelling and analysis [14]–[16]. From the single diode model of PV cell, the overall current generated by the PV cell can be represented mathematically using equation (1).

\[
I_{cell} = I_{PV,cell} - I_o \left( \frac{e^{V_{PV,cell} + I_{cell}R_s/\eta T} - 1}{I_{cell}R_s} \right)
\]

where, \(I_{cell}\) is the total terminal current generated by the PV cell in amperes (A), \(I_{PV,cell}\) is the photo current of the cell in amperes (A), \(I_o\) is the reverse saturation current of a diode in amperes (A), \(V_{PV,cell}\) is the voltage across PV cell in volts (V), \(n\) is the ideality factor, \(V_T\) is the volt temperature equivalent of the PV cell and \(R_s\) and \(R_{sh}\) are the series and shunt resistances of PV cell in ohms (Ω) respectively.

As the considered PV module consists of \(N_s\) number of PV cells in series (please refer Fig. 1), the mathematical representation of PV module can be given as in (2).

\[
I_{PV,M} = I_PV - I_o \left( \frac{e^{V_{PV,M} + I_{PV,M}N_iR_s/\eta T} - 1}{I_{cell}R_s} \right)
\]

where, \(N_sR_s\) and \(R_{sh}/N_s\) are the equivalent series and shunt resistances in ohms (Ω) respectively. In this paper, the considered PV module parameters are given in Table 2.

III. PV INTERCONNECTION SCHEMES, SHADING SCENARIOS AND IRRADIANCE LEVELS

The various interconnection schemes, shading conditions, and irradiance levels considered for the simulation and experimental analysis are presented in this section.

A. INTERCONNECTION SCHEMES

The well-known interconnection schemes like series (S), parallel (P), series-parallel (SP), total cross tied (TCT), honey comb (HC) and bridge link (BL) are considered for the investigation.

1) SERIES (S) INTERCONNECTION SCHEME

This is a basic interconnection scheme for all the different configurations considered. Here, the PV modules are connected in series to achieve the desired voltage level. A bypass diode in parallel with the PV module is used to protect the module from circulating currents under PSCs. This type of interconnection scheme is generally used in grid integrated PV systems. Fig. 2 presents the schematic representation of S interconnection scheme in 4×4 array. From Fig. 2, the overall voltage, current and power of the PV array are as given in (3),
FIGURE 2. Schematic representation of series (S) interconnection scheme in 4×4 array.

FIGURE 3. Schematic representation of parallel (P) interconnection scheme in 4×4 array.

FIGURE 4. Schematic representation of series-parallel (SP) interconnection scheme in 4×4 array.

2) PARALLEL (P) INTERCONNECTION SCHEME
In this interconnection scheme, all the PV modules are connected in parallel. i.e., the overall voltage of the array is same as the PV module voltage whereas, the overall current of the array is the summation of individual PV module currents. As the effect of PSCs on module voltage is very less (variation of PV module voltage under PSCs is negligible), the maximum power extracted under this scheme is very high. Nevertheless, the conduction losses are also very high as the overall current in the array is the algebraic sum of individual PV module currents.

Fig. 3 presents the schematic representation of P interconnection scheme in 4×4 array. From Fig. 3, the overall voltage, current and power of the PV array are given in (6), (7) and (8) respectively.

\[ V_{PV} = V_{PV1} + V_{PV2} + \ldots + V_{PV16} = \sum_{i=1}^{16} V_{PV,M} \]  
(3)

\[ I_{PV} = I_{PV1} = I_{PV2} = \ldots = I_{PV16} = I_{PV,M} \]  
(4)

\[ P_{PV} = V_{PV} \times I_{PV} \]  
(5)

3) SERIES-PARALLEL (SP) INTERCONNECTION SCHEME
This scheme is a combination of S and P interconnection schemes wherein, initially the PV modules are connected in series string to obtain the desired output voltage level and then these strings are connected in parallel to obtain a desired current levels. This type of interconnection scheme is most commonly used in commercial PV power generating plants as it is less complex, affordable and has fewer cross ties. All the PV modules connected in the string have a bypass diode across them to protect the modules from uneven current flow. These strings are connected with each other through a series diode across each string to protect the PV modules from circulating currents under PSCs. Fig. 4 presents the schematic representation of SP interconnection scheme in a 4×4 array.

From Fig. 4, the overall voltage, current and power of the PV array under this interconnection scheme can be given as in (9), (10) and (11) respectively.

\[ V_{PV} = V_{PV1} + V_{PV2} + V_{PV3} + V_{PV4} \]  
(9)

\[ I_{PV} = I_{string1} + I_{string2} + I_{string3} + I_{string4} \]  
(10)

\[ P_{PV} = V_{PV} \times I_{PV} \]  
(11)

4) TOTAL CROSS TIED (TCT) INTERCONNECTION SCHEME
This is a modified version of SP interconnection scheme wherein, initially the PV modules are interconnected in series and parallel manner to form the SP interconnection. Then, cross ties are introduced between the PV modules in the array such that, the entire row in the array is parallelly connected and such rows are connected in series. Therefore, the voltage of the array is equivalent to the summation of PV module
voltage connected in rows. The current of the array is equivalent to the summation of overall row currents connected in series. Fig. 5 presents the TCT interconnection scheme in a 4 x 4 array. From Fig. 5, the overall voltage, current and power of the PV array under this interconnection scheme can be given as in (12), (13) and (14) respectively.

\[
V_{PV} = V_{PV1} + V_{PV2} + V_{PV3} + V_{PV4} \quad (12)
\]

\[
I_{PV} = I_{PV1} + I_{PV5} + I_{PV9} + I_{PV13} \quad (13)
\]

\[
P_{PV} = V_{PV} \times I_{PV} \quad (14)
\]

5) HONEY COMB (HC) INTERCONNECTION SCHEME
This is a bio inspired interconnection scheme wherein, the PV modules are connected in a manner to represent the honey comb cell (i.e. the edges of a hexagonal geometry wax cells built by honey bees in their nest). In this interconnection scheme, three PV modules are connected in series and the combination is connected in parallel with other three series connected PV modules to depict the shape of a honey comb cell. This type of interconnection scheme has a better performance than the S, P and SP interconnection schemes in PSCs [17]. Fig. 6 presents the HC interconnection scheme in a 4 x 4 array. From Fig. 6, the overall voltage, current and power of the PV array under this interconnection scheme can be given as in (15), (16) and (17) respectively.

\[
V_{PV} = V_{PV1} + V_{PV2} + V_{PV3} + V_{PV4} \quad (15)
\]

\[
I_{PV} = I_{PV1} + I_{PV5} + I_{PV9} + I_{PV13} \quad (16)
\]

\[
P_{PV} = V_{PV} \times I_{PV} \quad (17)
\]

6) BRIDGE LINK (BL) INTERCONNECTION SCHEME
This is a bridge rectifier inspired scheme wherein, the PV modules are interconnected in a way that they form a shape of bridge rectifiers and these interconnections are connected with each other to form an array as shown in the Fig. 7. In Fig. 7, two PV modules are connected in series and then the combination is connected in parallel with other two series connected modules to form a bridge structure. This type of interconnection scheme has better performance than S, P and SP interconnection schemes in PSCs. The overall voltage, current and power of the PV array under this interconnection scheme can be given as in (18), (19) and (20) respectively.

\[
V_{PV} = V_{PV1} + V_{PV2} + V_{PV3} + V_{PV4} \quad (18)
\]

\[
I_{PV} = I_{PV1} + I_{PV5} + I_{PV9} + I_{PV13} \quad (19)
\]

\[
P_{PV} = V_{PV} \times I_{PV} \quad (20)
\]

B. SHADING CONDITIONS
On the 4 x 4 array, shading scenarios such as row shading, column shading, corner shading, center shading, diagonal shading and random shading are considered. In the row and column shading scenarios, two cases like single row/column and two row/column conditions are shaded as shown in Fig. 8 (a), 8 (b), 8(c) and 8(d). In case of corner shading, the top left corner of the PV array is shaded as given in the Fig. 8 (c). Under center shading scenario, the PV modules are shaded in center of the array as shown in Fig. 8(f). For diagonal shading conditions, the PV modules are shaded diagonally from left to right of the PV module as shown in Fig. 8 (g) and for the random shading scenario, the PV modules are shaded randomly which is shown in Fig. 8 (h).
C. IRRADIANCE LEVELS

Four irradiance levels such as 100 W/m², 300 W/m², 500 W/m² and 900 W/m² are considered to analyse the effect of irradiance change on PSCs in this paper. All the aforementioned interconnection schemes and PSCs are simulated, experimentally verified and analyzed under these irradiance levels. Fig. 9 presents the schematic representation of the considered irradiance levels.

IV. SIMULATION STUDIES

Simulations are carried out to obtain the P-V characteristics of the considered interconnection schemes with different PSCs and irradiance levels. MATLAB 2018a simulation software is used to carry out the simulations running on a desktop having i7 processor with 3.4 GHz processing speed and 16 GB RAM. A 4×4 array consisting of 16 PV modules are considered for the simulation studies with the ratings as given in Table 2.

Different PSCs such as single row shading (1R), two row shading (2R), single column shading (1C), two column shading (2C), center shading (CNTR), corner shading (CRNR), diagonal shading (DGNL) and random shading conditions (RNDM) are simulated for different irradiance levels and with different interconnection schemes for obtaining the P-V characteristics of the PV array. Fig. 10, Fig. 11, Fig. 12, Fig. 13, Fig. 14 and Fig. 15 present the P-V characteristics of the S, P, SP, TCT, HC and BL interconnection schemes at the said PSCs and irradiance levels of 100 W/m², 300 W/m², 500 W/m² and 900 W/m² respectively. It can be observed from the P-V characteristics that as the irradiance under PSCs decreases from high to low (i.e. 900 W/m² to 300 W/m²) value, the maximum power generated by the PV array also decreases. There exists multiple peaks at low irradiance levels of PSCs due to which the extraction of maximum power becomes tedious. It is also observed from the simulation results that the P interconnection scheme is least affected by various PSCs and irradiance levels. However, TCT and HC interconnection schemes have multiple peaks at very low irradiance levels. A detailed analysis of these simulation results is presented in the performance analysis section (Section VI).

V. EXPERIMENTAL VERIFICATION

To verify the accuracy of the P-V characteristics obtained from the simulations, an experimental verification is done by...
plotting the P-V characteristics of a real-time PV module having the ratings similar to that given in Table 2. Fig. 16 presents the snapshot of the experimental set-up wherein; CHROMA solar simulator is used to depict the PV array. This 4×4 array is configured with PV modules having the parameters as given in Table 1 to generate the required power and voltage. Variable resistive loads are used to vary the operating point of the PV array on P-V characteristics. LECROY MSO with data processing and analysis tool is used to process the voltage and current values and to plot the P-V characteristics.

For the experimental verification of P-V characteristics, results of only S interconnection scheme with PSCs at an irradiance of 500 W/m² are derived. Fig. 17 presents the P-V characteristics of the considered PV array obtained experimentally. Upon comparing the magnitudes, peak powers and number of peak points in P-V characteristics obtained from simulation (Fig. 10 (c)) and from the experimental results (Fig. 17), it can be seen that the simulated results are almost matching with the experimental results, thereby validating the simulations.

VI. PERFORMANCE ANALYSIS

To derive the effect of irradiance on power generation from PV array interconnection schemes under PSCs, the performance analysis is carried out in terms of maximum
FIGURE 17. Experimentally obtained P-V characteristics of S interconnection scheme with different PSCs at 500 W/m$^2$. (a) single row shading (b) single column shading (c) two row shading (d) two column shading (e) center shading (f) corner shading (g) diagonal shading (h) random shading. X-axis: 65 V/division, Y-axis: 100 W/division.

power generation ($P_{MPP}$), fill factor ($FF$) and mismatching power loss ($%ML$). The expressions for computing the FF and $%ML$ is represented as follows:

**Fill Factor** - It is the ratio of maximum power obtained from the PV array and the product of array open circuit voltage and array short circuit current. Mathematically, it can be expressed as given in (21).

$$FF = \frac{V_{MPP} \times I_{MPP}}{V_{OC} \times I_{SC}}$$  \hspace{1cm} (21)

Here, $V_{MPP}$, $I_{MPP}$, $V_{OC}$ and $I_{SC}$ are the overall array maximum power point voltage, current, open circuit voltage and short circuit current respectively.

$%ML$ - It is the power loss that occurs due to the mismatch in the current generated between the PV cells. It is given as the ratio of difference between the power generation at standard test condition and partial shading condition respectively, and the power generation at standard test condition. Mathematically, $%ML$ can be expressed as given in (22).

$$%ML = \frac{P_{STC} - P_{PSC}}{P_{STC}}$$  \hspace{1cm} (22)

Here, $P_{STC}$, $P_{PSC}$ are power generated from the PV array under standard test condition and partial shading conditions respectively.

A detailed analysis of the PSCs such as single row shading, two row shading, single column shading, two column shading, corner shading, center shading, diagonal shading and random shading conditions is carried out for different irradiance levels and interconnection schemes. The performance results of different interconnection schemes during the considered PSCs are presented in Fig. 18 to Fig. 25.

**A. ANALYSIS UNDER ROW SHADING CONDITION**

Under this condition, two cases are considered, single row shading and two row shading. Fig. 18 and Fig. 19 presents the performance results of different interconnection schemes during these PSCs. When entire row is shaded, it is observed that except for S and P interconnection schemes, SP, TCT, HC and BL have identical performance under all the considered irradiance conditions. Under this PSC, with an irradiance of 100 W/m$^2$, the S and P schemes have a maximum power generation of 356 W and 371.9 W, while the rest of the interconnection schemes have a maximum power generation of 352 W. Based on the practical operating conditions (i.e., voltage and current ratings), the S interconnection scheme is preferred over P interconnection scheme. The S interconnection scheme has better performance with the maximum $FF$ of 0.529 with least $%ML$ of 25.8%. For this PSC, at an irradiance of 300 W/m$^2$, the S and P schemes have maximum power generation of 356 W and 396.9 W and the rest of the interconnection schemes have a maximum power generation of 352 W. The S interconnection scheme displays the highest $FF$ of 0.522 and the lowest $%ML$ of 25.8%. Similarly, for the irradiance level at 500 W/m$^2$, the maximum power generation capability remains the same for all interconnection schemes as in the earlier case. However, for the PSC with an irradiance of 900 W/m$^2$, the S and P schemes produce maximum power of 459.6 W and 468.8 W respectively. The rest of the schemes generate a power of 455.8 W. The maximum $FF$ and least $%ML$ are observed in S scheme with 0.66 and 4.2% respectively. Identical to the single row shading, when two rows were shaded, similar performance is noted. Further, due to two rows getting shaded, the reduced power generation by all interconnection schemes is observed. S interconnection scheme has better $FF$ of 0.352, 0.344, 0.394 and 0.650 at irradiance levels of 100 W/m$^2$, 300 W/m$^2$, 500 W/m$^2$ and 900 W/m$^2$ respectively. The $%ML$ is observed as 51.66%,
51.66%, 43.95% and 6.29% for the considered irradiance variations.

**B. ANALYSIS UNDER COLUMN SHADING CONDITION**

Under this condition, two cases are considered, single column shading and two column shading. Fig. 20 and Fig. 21 presents the performance results of different interconnection schemes under this PSC. When an entire column is shaded, it is observed that, except for S and P interconnection schemes, SP, TCT, HC and BL have shown similar performance. For this PSCs at an irradiance of 100 $W/m^2$, the S and P schemes have maximum power generation of 356 W, 371.9 W, while the rest of the interconnection schemes have a power generation of 368.8 W. Based on the practical operating conditions (i.e., voltage and current ratings), the TCT interconnection scheme has better performance and gives maximum $FF$ of 0.694 and least $%ML$ of 23.16%. For the PSCs at an irradiance of 300 $W/m^2$, the S and P schemes have maximum power generation of 356 W, 393.6 W, while the rest of the interconnection schemes have a power generation of 393.6 W and 396.9 W respectively, while, the rest of the interconnection schemes generate 393.6 W. The maximum $FF$ of 0.690 is observed in the TCT scheme with the lowest $%ML$ of 18%. Similarly, with this PSC under the irradiance of 500 $W/m^2$, the maximum power generation capability remains the same for all interconnections as it is at 300 $W/m^2$. For the irradiance level at 900 $W/m^2$, the S and P schemes generate 459.6 W and 468.8 W respectively, and the rest of the schemes generate 464.9 W. The maximum $FF$ and least $%ML$ are observed in TCT scheme with 0.689 and 3.14% respectively. As identical to single column shading, when two columns are shaded, similar performance is observed for all the interconnection schemes with reduced power generation. TCT interconnection scheme has a better $FF$ of 0.705, 0.704, 0.702, and 0.693 at irradiance levels of 100 $W/m^2$, 300 $W/m^2$, 500 $W/m^2$ and 900 $W/m^2$ respectively. The $%ML$ is found to be 45.47%, 35.16%, 24.97% and 5.45% for the above considered irradiance levels.

**C. ANALYSIS UNDER CENTER SHADING CONDITION**

The performance results of different interconnection schemes under this PSC are presented in Fig. 22. It is observed from the Fig. 22 that TCT and BL interconnection schemes have similar performance under this PSC. For this PSC at an irradiance of 100 $W/m^2$, the S, P, SP, TCT, HC and BL schemes have maximum power generation of 356W, 371.9W, 263.8W, 287.6W, 275.2W and 287.6W respectively. Based on the practical applicability, the S scheme has performance with maximum $FF$ of 0.529, least $%ML$ of 25.83%, and operating at $V_{MPP}$ and $I_{MPP}$ of 285.6 V and 1.24 A respectively. For this PSC at an irradiance level of 300 $W/m^2$, the S, P, SP, TCT,
HC and BL schemes generate maximum power of 356W, 396.9W, 315.5W, 336.8W, 325.7W and 336.7W respectively. It can be inferred that the S interconnection scheme has better performance as compared to others with a FF of 0.522 and %ML of 25.83%, with $V_{MPP}$ and $I_{MPP}$ of 286V and 1.24A respectively. However, for an irradiance of 500 W/m², the S, P, SP, TCT, HC and BL schemes generate a maximum power of 356W, 421.5W, 366.8W, 383.5W, 374.9W and 383.5W respectively. TCT and BL interconnection schemes show better performance with a FF and %ML of 0.557 and 20.10% respectively with $V_{MPP}$ and $I_{MPP}$ of 99.04V and 3.87A respectively. Similarly, for an irradiance of 900 W/m², the S, P, SP, TCT, HC and BL schemes generate a maximum power of 459.6W, 468.8W, 460.8W, 462.8W, 461.6W and 462.8W respectively. TCT and BL interconnection schemes are found to give better performance with a FF and %ML of 0.672 and 3.58% respectively, at $V_{MPP}$ and $I_{MPP}$ of 95.65V and 4.83A respectively. Therefore, it can be inferred that - under this PSC, with the variation in irradiance, the performance of each of the interconnection scheme varies.

D. ANALYSIS UNDER CORNER SHADING CONDITION

The performance results under this PSC at different irradiance levels is presented in Fig. 23. For this PSC at an irradiance of 100 W/m² the S, P, SP, TCT, HC and BL schemes generate a maximum power of 356W, 273.1W and 278.4W respectively. Based on the practical applicability, the S scheme provides better performance with a maximum FF of 0.528 and least %ML of 25.83%. The $V_{MPP}$ and $I_{MPP}$ are observed to be 286.1 V and 1.24 A respectively. For this PSCs at an irradiance level of 300 W/m², the S, P, SP, TCT, HC and BL schemes generate maximum power of 356W, 396.9W, 315.5W, 336.8W, 324.9W and 329W respectively. With a FF of 0.522 and %ML of 25.83%, S interconnection scheme has better performance in comparison to the rest of the schemes. The $V_{MPP}$ and $I_{MPP}$ are observed as 286 V and 1.24 A respectively. However, for an irradiance of 500 W/m², the S, P, SP, TCT, HC and BL schemes generate a maximum power of 356W, 421.5W, 367W, 383.5W, 374.9W and 377.7W respectively. The TCT interconnection scheme show better performance with a FF and %ML of 0.670 and 3.58% respectively. The $V_{MPP}$ and $I_{MPP}$ are observed to be 95.65V and 4.83A respectively. From the above analysis, it can be inferred that - under this PSC, with the variation in irradiance, the performance of each of the interconnection scheme varies.
E. ANALYSIS UNDER DIAGONAL SHADING CONDITION

The performance results under this PSC is presented in Fig. 24. It can be observed from Fig. 24 that TCT and BL interconnection schemes have similar performance. For an irradiance of 100 W/m², the S, P, SP, TCT, HC and BL schemes generate maximum power of 356W, 371.9W, 352W, 368.8W, 293.1W and 368.8W respectively. Based on the practical operating conditions (i.e., voltage and current ratings), the TCT and BL schemes exhibit better performance with maximum FF of 0.696 and least %ML of 23.16%. The V_{MPP} and I_{MPP} are observed as 94.9 V and 3.88 A.

For 300 W/m², the S, P, SP, TCT, HC and BL schemes generate maximum power of 356W, 396.9W, 352W, 393.6W, 324.7W and 393.6W respectively. With FF of 0.698 and %ML of 18%, TCT and BL interconnection schemes have better performance in comparison to other schemes. The V_{MPP} and I_{MPP} for TCT are observed as 95.4V and 4.12 A respectively. However, for 500 W/m² irradiance, the S, P, SP, TCT, HC and BL schemes generate maximum power of 356W, 421.5W, 352W, 418W, 374.4W and 418W respectively wherein, the BL interconnection scheme has better performance with FF and %ML of 0.694 and 12.19%.
respectively. The $V_{MPP}$ and $I_{MPP}$ are observed as 95.53V and 4.37A respectively. Similarly, for 900 W/m², the S, P, SP, TCT, HC and BL schemes generate a maximum power of 459.6W, 468.8W, 455.8W, 464.9W, 462.2W and 464.9W respectively. The TCT and BL schemes show better performance with $FF$ and $%ML$ of 0.695 and 3.14% respectively. From the above analysis, it can be inferred that - under this PSC, with the variation in irradiance, the performance of each of the interconnection scheme varies.

**F. ANALYSIS UNDER RANDOM SHADING CONDITION**

The performance results under this PSC at different irradiance levels is presented in Fig. 25. For an irradiance of 100 W/m², the S, P, SP, TCT, HC and BL schemes generate maximum power of 263W, 290.9W, 233.4W, 214.1W, 204.3W and 217.4W respectively. Based on the practical operating conditions (i.e., voltage and current ratings), the S scheme exhibits better performance with maximum $FF$ of 0.397 and least $%ML$ of 45.20%. The $V_{MPP}$ and $I_{MPP}$ are observed as 210.8 V and 1.24 A. For an irradiance of 300 W/m², the S, P, SP, TCT, HC and BL schemes generate maximum power of 263W, 334.6W, 233.4W, 259.4W, 242.5W and 253.5W respectively. With $FF$ of 0.390 and $%ML$ of 45.20%, S interconnection scheme has better performance as compared to the rest of the schemes. The $V_{MPP}$ and $I_{MPP}$ are observed to be 211.7V and 1.24A respectively. However, with the irradiance of 500 W/m², the S, P, SP, TCT, HC and BL schemes generate maximum power of 272.2W, 377.7W, 269.4W, 333.1W, 279.9W and 287.3W respectively. With $FF$ and $%ML$ of 0.556 and 30.60%, the TCT interconnection scheme shows a better performance. The $V_{MPP}$ and $I_{MPP}$ are observed to be 101.2 V and 30.29 A. Similarly, for an irradiance of 900 W/m², the S, P, SP, TCT, HC and BL schemes generate maximum power of 452W, 460.4W, 448.5W, 454.8W, 449.3W and 450.7W respectively. The TCT scheme exhibits better performance with a $FF$ and $%ML$ of 0.681 and 5.25% respectively. The $V_{MPP}$ and $I_{MPP}$ are observed as 95.78V and 4.74A. From the above analysis, it can be inferred that - under this PSC, the performance of each of the interconnection schemes will vary with irradiance variations.

From the performance results, it is observed that under low irradiance PSCs, the S and SP interconnection schemes give better performance while under medium and high irradiance conditions TCT, BL and HC interconnection schemes perform better in comparison with the other schemes. Finally, it can be concluded that, for different PSCs and irradiance levels choosing one interconnection scheme to perform optimally under all conditions is not feasible. Hence, based on the partial shading and irradiance levels, electrical interconnections can be varied dynamically for maximum power extraction from the SPV.

**VII. CONCLUSION**

In this paper, a detailed investigation on the effect of irradiance change on maximum power generation from the PV interconnection schemes under different PSCs is performed. A 4×4 PV array is considered and P-V characteristics of the array under S, P, SP, TCT, HC and BL interconnection schemes for six partial shading scenarios at four distinct irradiance levels are simulated, experimentally verified and analyzed. A detailed performance analysis of the PV interconnection schemes under PSCs is presented to study the effect of irradiance on power generation in different interconnection schemes. From the simulation studies and detailed performance analysis, it is concluded that -

- During PSCs, the magnitude of irradiance change on PV array interconnection schemes has great impact on the power generation, as the peak power generation depends on the irradiance magnitude for the considered PSCs.
- No direct relationship can be established for determining the optimal array interconnection scheme since each PV interconnection scheme performs antithetically under different PSCs and irradiance conditions.

Moreover, it is observed that under PSCs with low irradiance, the S and SP interconnection offers better performance while, under medium and high irradiance conditions TCT, BL and HC interconnection schemes offer good performance as compared to others. It is also inferred that while designing a PV system, rigorous studies need to be done before carefully selecting the suitable interconnection scheme. This
can be carried out by dynamically altering the electrical interconnections.

Further, as a future work a detailed study can be carried out on various interconnection schemes for effectively mitigating the multiple peaks and to extract maximum power from the PV module under all PSCs.

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