MATLAB-Based Simulation Analysis of the Partial Shading at Different Locations on Series-Parallel PV Array Configuration

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MATLAB-Based Simulation Analysis of the Partial Shading at Different Locations on Series-Parallel PV Array Configuration

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Abstract: The photovoltaic (PV) have their installations in outdoor conditions where they face several unfavorable conditions and one of them is shading. One form of shading is partial shading that create mismatch among solar PV cells consequently disturbing electrical outputs and performance of a PV array output and hence power losses are created. A lot of information can be gathered just by observing the shape and magnitude of the curves obtained from I-V & P-V characteristics of the photovoltaic array. The I-V & P-V characteristics under shading also show changes in their usual shape which is analyzed in our research paper using MATLAB/Simulink-based simulation results by examining the variation in the characteristics of a series-parallel photovoltaic array configuration under partial shading conditions. The simulated results show existence of multiple peaks and steps in the I-V & P-V characteristics. The second part of result section show a comparative study among different partial shading condition and the mismatching power loss is estimated to be 27.16%, 29%, and 42.8% for partial shading pattern cases 2, 3, and 4, respectively. This paper will help readers and researchers with a clear idea of what shading is and how it affects the output of photovoltaic systems with a change in shading.

Keywords: Solar photovoltaic, Partial Shading, I-V & P-V characteristics, MATLAB/ Simulink, Power losses.

1. Introduction

Enormously increasing prices of energy, diminishing fossil fuels and growing pollution are among few important reasons to shift on renewable energy resources. A lot of renewable energy sources are available in nature, among them, solar energy, or solar photovoltaic energy, has proven to be a sustainable energy source. The paramount features of solar energy include continuous free abundant supply, clean energy source, including no moving parts in its conversion system, and pursue diverse applications.

As reported by one of the renowned organization IEA [International Energy Agency], generation by solar photovoltaics has increased from 156 TWh in 2020 to 821 TWh. Solar PV came will also be upcoming low-priced cost option for electricity generation in the world[1]. In 2021, despite the second continuous year of COVID-19, there is still growth observed in the PV market. According to one report, the total cumulative installed capacity for photovoltaic systems reached 942 GW by the end of 2021. The top three global PV markets were run by China with 54.9 GW of PV installations, followed by the USA with 26.9 GW of PV installations, and the third position was held by the European Union with 26.8 GW of installations in 2021.

China led by acquiring total installed capacity of 308.5 GW, which is about one-third of the world's total installed capacity[2,3]. Figure 1 represent the information of the top 10 countries in terms of annual PV installed capacity and total capacity for the year 2021. A solar cell, also widely recognized as photovoltaic cell performs the real job of generating electrical energy from the solar energy[4,5]. As the photovoltaic array has to be installed outdoors, it deals with many factors which may affect its output. A few such factors include heat, humidity, solar irradiation intensity, wind speed, temperature, the angle of the fall of the sun rays, and many more [6].

Primarily, solar irradiation and temperature turned out to be the most determining parameters and may cause the aging and degradation of laminations, corrosion, and other deteriorating effects on the performance of PV systems.

TABLE 1: TOP 10 COUNTRIES FOR INSTALLATIONS AND TOTAL INSTALLED CAPACITY IN 2021

FOR ANNUAL INSTALLED CAPACITY			FOR CUMULATIVE CAPACITY		
1	China	54,9 GW	1	China	308,5 GW
2	USA	26,9 GW	(2)	European Union*	178,7 GW
(3)	European Union*	26,8 GW	2	USA	123 GW
3	India	13 GW	3	Japan	78,2 GW
4	Japan	6,5 GW	4	India	60,4 GW
5	Brazil	5,5 GW	5	Germany	59,2 GW
6	Germany	5,3 GW	6	Australia	25,4 GW
7	Spain	4,9 GW	7	Italy	22,6 GW
8	Australia	4,6 GW	8	Korea	21,5 GW
9	Korea	4,2 GW	9	Spain	18,5 GW
10	France	3,3 GW	10	Vietnam	17,4 GW

Fig.1: List of top 10 countries for annual PV installed capacity and cumulative capacity in 2021[2].

In Shading scenario one or more cells are exposed to lesser irradiation than other cells present in a photovoltaic setup. Thus, under shading phenomena, the solar irradiation level received by the entire PV module surface is not uniform. As a consequence of shading, there may arise some alterations in the output by the PV system. The fundamental procedure to examine the repercussion of shading is to interpret the changes occurring in the shapes of curves of two chief characteristics named by current-voltage (I-V) & power-voltage (P-V) characteristics of a shaded PV array. According to the hypotheses, on shading a PV module with attached bypass diode, the curves of P-V characteristic are seen with several peaks or notches and there is exist only one global maximum power point (GPP) among all the peak, on which the entire photovoltaic system functions[7,8]. Hence, just by analyzing these characteristics a lot of information can be gathered about partial shading. Shading could be partial or complete shading. Partial shading is a critical reason observed for mismatching among the PV cells[9] and affects the power generation competence and efficiency. Partial shading is a shading condition that may arise due to cloud shading, deposition of dust, or neighboring structures like trees, chimneys, etc.[10].

Primarily, section 4 of this research work comprises of explanations to the theories pertaining to shading and the simulation results verifying the theories in the form of graphs using MATLAB/Simulink. The deterioration in power output depends on the shaded area and the irradiance from the sun. Hence, it is essential to diagnose the impact of shading and reduce the shading effect on PV systems[11,12]. Hence, in this research paper, MATLAB/Simulink-based simulations results are used to examine in depth the impact of partial shading. This paper research about how severely the shading impact the proper working of the solar PV, so that more ways can be worked upon for easy and early identification of the hotspots conditions due to partial shading and to mitigate the fluctuations in the outputs of PV panel.

2. Modelling basics of solar cell

2.1 Single Diode Model

A lot of electrical equivalents circuit of photovoltaic cell is available in the literature and the most recurrently studied model is the single diode model. The equivalent circuit of the single diode model is signified by current source I_{ph}, a diode D, a series resistance R_{se}, a parallel resistance Rp is represented in figure 2[13].

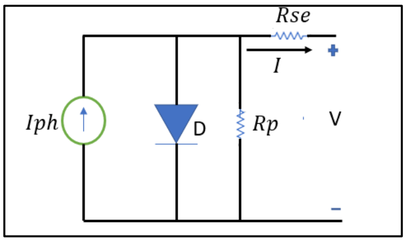


Fig. 2: Single diode model of a discrete PV cell.

Equation 1 describes the relationship between output Voltage - Current of a photovoltaic cell. The parameters include:
I_{ph} is known as photogenerated current,
I_{sat} is the PV cell dark saturation current.
T_o is the PV cell operating temperature in Kelvin is represented.
k is the Boltzmann constant (1.381×10^{-23} J/K),
q is the electron charge
A is the constant known as diode ideality constant,
Rp , R_{se} denotes the shunt and series resistance respectively.
The PV cell output current symbolized by I,(Ampere) and output voltage by V, (Volt).

$$I = I_{ph} - I_{sat}\left[\exp\left(\frac{q}{kT_oA}(V + IR_{se})\right) - 1\right] - \frac{(V+IR_{se})}{R_p} \quad (1)$$

$$I_{ph} = \left(I_{sh} + K_{Tsh}(T_o - T_r)\right)\frac{G_s}{G_{STC}} \quad (2)$$

Where,

I_{sh} is the short current of the cell at standard test condition (STC), at 25^{0}C and 1000 watts/m^2 .
K_{Tsh} is the short circuit temperature coefficient of the PV cell.
T_r is the reference temperature of the cell.
G_s is the solar irradiation and G_{STC} is the solar irradiation at STC[14].

$$I_{sat} = I_{rs}\left[\frac{T_r}{T_o}\right]^3 exp\left[\frac{qE_G}{kA}\left(\frac{1}{T_r} - \frac{1}{T_o}\right)\right] \quad (3)$$

Where,
I_{rs} denotes reverse saturation current of photovoltaic current at a reference solar irradiation and temperature.
E_G is the band-gap energy of semiconductor is given by photovoltaic cell is manufactured[15,16].

A Photovoltaic module is a protective packed and properly laminated setup of a series and parallel connection of PV cells circuit. One or more PV module are coupled to form a PV panel and this assembly of panels forms a complete generating unit called a PV array as displayed in Figure 3.

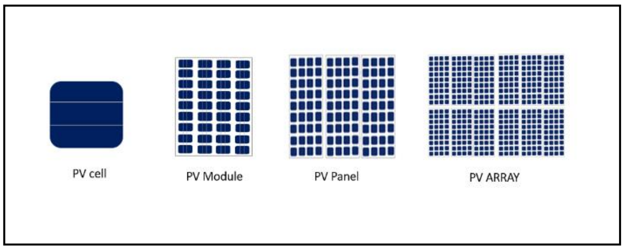
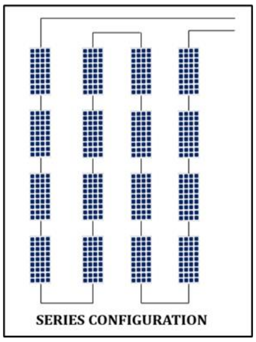
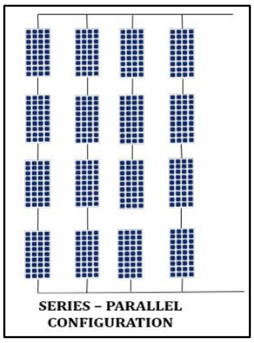
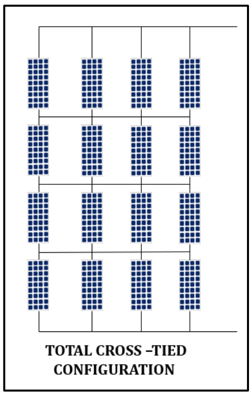


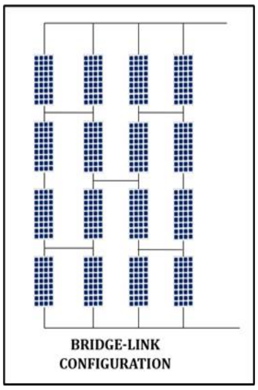
Fig. 3: Representation of complete generating unit starting from PV cell to PV array

Additional to shade intensity, array size and configuration are two critical factors that affect array output. When the intensity of shade is low and the variation of shade across the PV array is small, the output does not fluctuate much but then when solar irradiance subjected to the module varies over a wider range, the configuration and size of PV array turn out to be an important consideration. There has been a lot of research done to examine the relationship between array configuration, shading pattern, and intensity[17]. Multiple array topologies available for PV array configurations as shown in figure 4[18].









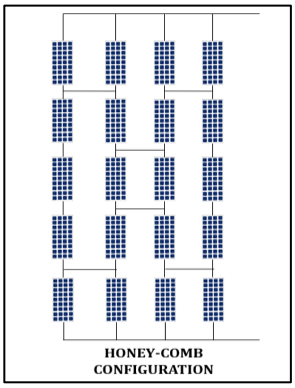


Fig. 4: Depiction of different topologies available for PV array

2.2 Understanding I-V & P-V characteristics of the PV array under partial shading conditions.

Primarily it is essential to know the operation of a basic photovoltaic cell subjected to uniform solar irradiance and partial shade conditions one after another and assess the curves of I-V & P-V characteristics by creating a simple MATLAB/Simulink model.

In MATLAB/Simulink under the Simscape environment, figure 5 depicts the simulation model of two PV cells connected in series where both the cell receives the same 1000 watts/m^2 of irradiance and without any bypass diode connection.

The figure 6a displays the output I-V & P-V curves under these conditions and show the original shape of the curves as represented in literature and many pieces of research[19].

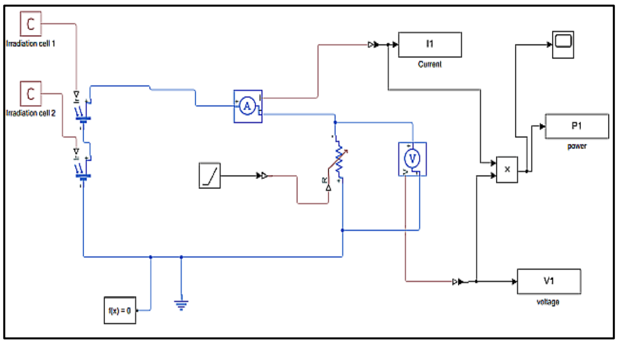
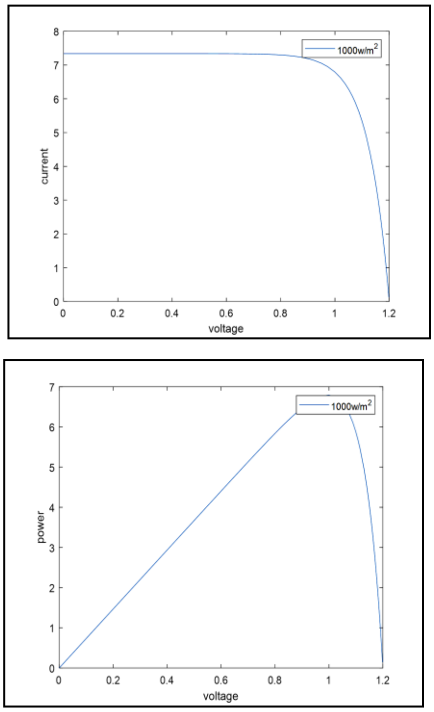
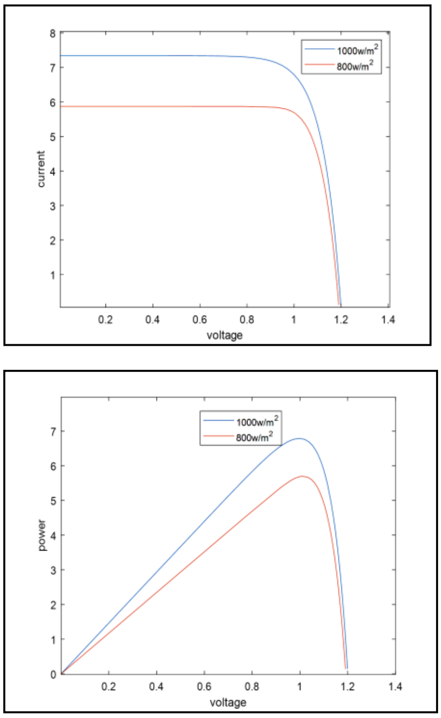


Fig. 5: MATLAB/Simulink model representation with Simscape tool of two series connected Photovoltaic cells in MATLAB/Simulink

However, if the solar irradiation received by two series-connected photovoltaic cells varies for an example 1000 watts/m^2 as denoted by irradiation cell 1 and 800 watts/m^2 as represented by irradiation cell 2 respectively with no bypass diode connected across them, the I-V & P-V graphs show changed response in the magnitude. As shown in figure 6b, there exist a discernible decline in the outputs shown in I-V & P-V curves.



(a)



(b)

Fig. 6: I-V & P-V curve results under two conditions (a) when both the series connected, cells are subjected to equal irradiation of 1000 watts/m^2 (b) one of the two PV cells is subjected to irradiation of 1000 watts/m^2 while the other one receives solar irradiation of 800 watts/m^2

As there is no bypass diode, there is no change in the shape of the curve. Figure 6b indicates that the magnitude of generated power dropped substantially as solar irradiance on one of the PV cells tends to decrease. This represents the connection among the generated power and output voltage when one PV cell is under shade.

2.3 Interpreting the shapes of I-V & P-V curves

The deviation in shape and magnitude of measured I-V & P-V curves from original curves can be one of the following types:

1. Curve with low short circuit current (Isc): Curve with lower Isc than expected I-V curve may occur due to solar cell receiving inadequate irradiance or shading, soiling, or operator error.
2. Curve with low open-circuit voltage (Voc): Curve with lower Voc than expected I-V curves may result from hardware problems, inaccurate cell temperature measurement, or shading.
3. Notched or stepped I-V curve: The curve's steps are mainly owing to current mismatch in different cells, modules, or array regions. The notches or steps occur during the bypass diode activation, compelling the current to pass from the module's weaker cells. The current mismatch can be influenced by a lot of factors, including current mismatch, soiling, shading, and damaged cell. When all PV cell in a module receive have the identical amount of solar irradiance, the curves exhibit a single maximum power point[20)]. However, distinct to this during partial shading conditions, where PV cells or modules are shaded and receive a lesser amount of solar irradiation, the PV system create multiple maximum power points in the P-V curve and steps in the I-V curve[21)]. Stepped curve result from damaged PV cells as well.

The deviations in the shape of the P-V curve of PV array output as a consequence of partial shading is well explained by figure 7.

1. Point 1 represents the actual curve shape under uniform solar irradiation and there is a complete absence of shading.

2. Point 3 depicts the significant drop in the magnitude of P-V curve but shape of the curve remains same while the modules are not connected to a bypass diode and are under partial shading conditions.
3. While the partially shaded PV array with a bypass diode connected to a module develops notches or peaks as shown by point 2 with multiple local maximum power points or LPP and distinct GPP called global maximum power point.

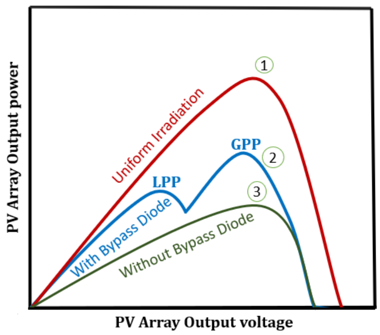


Fig. 7: Representation of different possible outcomes of P-V characteristic under shading.

3. Fundamentals of shading and its impact on the solar photovoltaic – Literature Review

A PV module is a single, self-contained unit used to extract electrical energy from sun irradiation. Many parameters including environmental conditions regulate the output of a PV module. Shading can be defined as the obstruction of solar irradiation caused by any object that causes shadows. The shading is classified as static shading for the slow change in irradiance, or as dynamic shading because of the quick change in solar irradiance. Soft and hard shading is other categories of shading. Soft shading is uncontrolled and results from distant objects such as clouds. The second type of shading is caused by solid objects placed close to the solar panel, such as chimneys, flues, leaves, dirt, trees, birds, bird droppings, other roof areas, antennas, etc. called hard shading. The shading by the clouds still allows diffused solar radiations to reach the panel, allowing for adequate power generation, whereas the hard shading blocks more sunlight from reaching the affected area. Shading may result in unintended side effects and harm to a panel, resulting in even long-term deterioration. A solar PV system is so designed to generate the maximum amount of power under available solar radiation and temperature conditions by incorporating a device such as an MPPT along with PV arrays[22,23)].

The power losses get influenced by factors like shape and size of the shadow on PV, geometrical and electrical design of cells and arrays, and how the shadow drops on the module[24,25)]. The problem of shading has been a point of concern from a very early time. In 1965 Ralph M. Sullivan suggested shading as a complicated issue in space satellites leading to output power loss. A PV module under shading does not receive full solar irradiation. Partial shading and complete shading are two types of shading a module can experience. In both the cases of shading the shape of I-V & P-V curve develop dissimilarities than original curves under partial shading conditions further signifying a kind of losses or degradations in the PV[26)]. The two important curves I-V & P-V characteristics that describes PV array properties consequently get disturbed when shaded, resulting in multiple peaks rather than a single maximum peak[27)]. Two research papers concluded that partially shaded PV panels as a major hindrance in the progress of solar PV systems[28,29)]. A study presented the impact of partial shading through MATLAB simulations and concluded that along with the array size, the array configuration remarkably impacts the energy yield[17)]. A thorough simulation procedure and modeling of solar cells and PV modules in the partially shadowed condition has been presented by an author in the PSpice environment demonstrating the significance of incorporating various bypass diode configurations into a PV module[30)].

The output from a photovoltaic system is critically affected by the type and characteristics of shading, array configuration, and the presence of a diode bypass diode. The consequences of full and partial shading are experimentally analyzed using Gray and Black foils on PV modules to create shade. In both the conditions of total and partial shading, the I-V characteristics exhibited a significant decline. The result show, the decline in the short circuit current from 8100 to 100 mA along with deterioration in the complete PV system power[31)]. One of the most important things that affect how well a solar PV cell works is how much sunlight hits cell[32,33)]. Through an experimental setup the author noted a drop in generated power of 30% just by shading single PV cell by 50%[34)]. The study described the fluctuations in power generation caused by PV shade caused by passing clouds[35)]. The author analyzed the impact of passing clouds on a grid-connected PV system with battery storage employing the newest neural network model[36)]. The observations are also done on dust-induced shading and reported 28.6% and 28.5% reduction of PV output at the same dust density on C-Si and CIGS technologies respectively[37,38)]. One of the major issues affecting the PV cells and modules is the formation of the hotspot, generally marked by the presence of a localized over-temperature portion of solar cell[39,40)]. Temperature can rise even by partial shading in a very small area of a cell or a module.

The solar PV cell becomes reverse biased under partial shading conditions, resulting in power dissipation rather than a generation and localized heating. To limit such conditions a bypass diode is been incorporated with the PV modules. A vast research study is available and concludes that shading causes hotspot development thus dropping the corresponding photogenerated current[41)]. However, extensive research has been going on to reduce the impact of the hotspot, one such research experiment made use of distributed MPPT approach to minimize the hotspot created by a partially shaded module and resulted in lowering of module temperature by 20°C for small shadows[42,43)]. The temperature distribution is again one of the most vital concerns and may have short-term and long-term upshot on the electrical output parameter. Also, the authors created an electro-thermal model in the PSpice environment to examine temperature distribution under shaded PV module where the output from shaded module is evaluated on account of number of shaded cells, shaded area, and the temperature distribution using an experimental setup[44]. Researchers and academicians are currently focusing on the effect of partial shade on the most recent shingled module technologies as well and studying the impact of shading on power losses and the potential development of heat and hotspot in these PV modules[45].

By experimental research, the author reported a temperature increase of 145^0C at partial shading at a shading ratio of 60% and also noted that shingled PV module technologies are more prone to hotspot development than traditional half-cell modules[46,47].The author also studied the effect of partial shading through model simulation in LT-Spice and experimental setup of half-cell modules and full-cell modules and found that half-cell modules showed a better performance and better outputs power. So, partial shading is related to the amount of shaded area, and the generation of solar photovoltaics can be better by making changes to the design and layout[48]. The study also reported a higher possibility of PV failure in over-lapping bypass diode configuration leading to a greater power loss in comparison with non-overlapping bypass diode model due to shading[49]. The PV array design and bypass diode configuration may also affect the hotspot developed due to mismatch or shadow on the PV module. Various bypass diode configurations are explored in a research study through experimental and simulation setup to lessen shadowing or mismatching influence on the PV module[50]. In severe cases, the rise in temperature due to shaded photovoltaic and the development of hotspots may even endanger the module's performance and entire life[51].

Solar irradiation and temperature being crucial parameters that influence the generated output, the author propose the study of partial shading detection, analyses of P-V curve, and algorithm for global MPPT. The proposed new algorithm is divided into three steps which comprise of the main program, shading identification and maximum power point tracking. The work includes mathematical equations and successful simulations results of proposed algorithm with reduction in loss of power with each tracking step[8]. Another study performed comparison analysis of the power outputs from conventional by pass diode and power electronics based DPP converter used along with different types of configurations of 4*4 PV array. The system is analyzed at different solar irradiations using PSIM software. The simulation results exhibited DPP based architecture as a promising solution to improvise the energy yield during partial shading. But the over cost of PV system also increased[52]. The research study implemented in MATLAB/Simulink simulations presented a novel PV array arrangements leading to lessening the effect of partial shading by enhancing power output and eradicating the existence of multiple peaks in the power voltage curve under various partial shading conditions. The results showed improved performance from convention PV array configuration with elimination of multiple peaks and improving power outputs[53]. Implementing new designs and novel power electronics devices can make the PV system expensive is one major gap observed in the literature[52]. Secondly the PV model implementation in MATLAB/Simulink requires systematic knowledge of these software is yet one challenging task for the user[54]. Authors also presented new methods which minimize hotspots by 17% in shaded solar cells in addition to minimizing power loss in whole of PV system[55]. Various new techniques such as Impedance Spectroscopy have been used to identify the level of degradation by analyzing the ac parameters of solar cell[56].The performance of solar cell under different shading ration and shading pattens is identified by performing experimental study on mono and poly crystalline solar panels[57].Condition like shading still impacts the output power even after adopting various MPPT techniques, thus certainly it is not a healthy phenomenon for the entire PV system. This study aims as to evaluate the effect of shading phenomena so that there could be better ways searched out to minimize the impact of shading and increase the reliability and durability of a PV module. Hence, with the review it can be concluded that shading is one kind of problem faced by terrestrial solar photovoltaics. Therefore, it become very crucial to comprehend the working and behavior of photovoltaic under shading circumstances.

4. Simulation results

This part analyses the modeling of a 3×2 series-parallel PV array, where photovoltaic modules are primarily linked in series to form a string to get the desired voltage and then parallel connection is done to acquire the needed current. Two parallel columns or strings S1 and S2 each have 3 series-connected PV Modules M11, M12, M13, and M21, M22, and M23 respectively. This section uses modelling of series-parallel PV array with MATLAB-R2020a to understand the behavior of PV array through studying the I-V & P-V characteristics of the model under test[58]. The MATLAB/Simulink lacks a single PV module block. To solve this, the parameter of the PV array block is operated by making small changes like setting the parallel string to 1 and the series-connected module is set to 1. In this way, the PV array size is set to 1×1 implying that this block will be used as a single PV module. Each module has two constant blocks, one for solar irradiance and the other for temperature. The simulation results are analysed to investigate the functioning of solar array under varying solar irradiance, shading location by observing the changes occurring in the curves of I-V & P-V and to assess the performance of the PV array by calculating mismatching power loss in the latter part of this section. Figure 8 illustrates the 3×2 series-parallel PV array MATLAB/Simulink simulation model. The work is presented using MATLAB software as it is mostly used by academicians, researchers, and industrial organizations making it easy to understand the readers. An antiparallel bypass diode is also incorporated to protect each module. Under uniform solar irradiation and partial shade, a series-parallel PV array architecture is tested for I-V & P-V characteristics in the proposed model given in figure 8. 1000 watts/m^2, 700 watts/m^2, and 400 watts/m^2 of solar irradiation are used to generate three types of shading circumstances on PV modules.700 watts/m^2 and 400 watts/m^2 indicate shading severity subjected to the model at 25^{0}C where solar irradiations of 700 watts/m^2 represent the mild shading and 400 watts/m^2 represent the severe shading of the modules[59)].

KD Solar KD20013A2 polycrystalline modules are employed in the presented our simulation model. Due to simplicity and easy interpretation the influence of shading using the I-V & P-V characteristics has been previously analysed in many researches[60,61)].
The modules at different string locations are subjected to partial shading of 700 watts/m^2 and 400 watts/m^2. The output demonstrates that shading PV modules with any shading pattern cases reduces output power. The first simulation is carried out where none of the module in the array is under any kind of partial shading and is subjected to standard solar irradiation and temperature. Under total absence of shade and with standard solar irradiation and temperature, the PV array's maximum power output generated is 1,207 watts. In the obtained graphs, the presence of a bypass diode results in the formation of several peaks in P-V graphs and many steps in I-V graphs and is supported by literature available[62)].

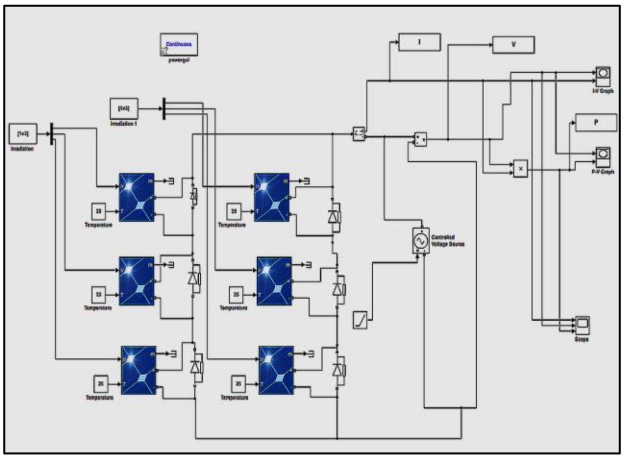


Fig 8: 3 × 2 series-parallel PV configuration under test

However, the novelty of this paper identifies how the shading as different locations and different intensities of solar irradiation together impact the characteristics curves supported by the calculated results from mismatching power loss ΔP_{Loss} (%) especially on much used polycrystalline PV module type technology.

The novelty the paper presented is to determine how shading impact the electrical characteristics of PV array when modules are subjected to variety of shading conditions clearly specifying the behavior of shaded modules by implementing the proposed model under MATLAB/ Simulink. This study will guide the researchers to pursue knowledge on partial shading and it will help to develop more efficient MPPT by understanding the characteristics obtained from the different partial shading conditions. KD solar 20013A2 is a practical polycrystalline PV module available and there it can be easily demonstrated practically and the details of the module is available with link[63)]. Simulations based on practical module helps in short term and long-term studies and proposed model can be built for practical PV system. Figure 9 is a pictorial representation of the different location of PV modules subjected to partial shade on the PV array under test and it is clearly visible that three shading patterns representing case 2, 3, and 4 and is compared with no shading condition in case 1. Testing conditions are discussed under part "A" and "B"

(A) Under uniform irradiance conditions

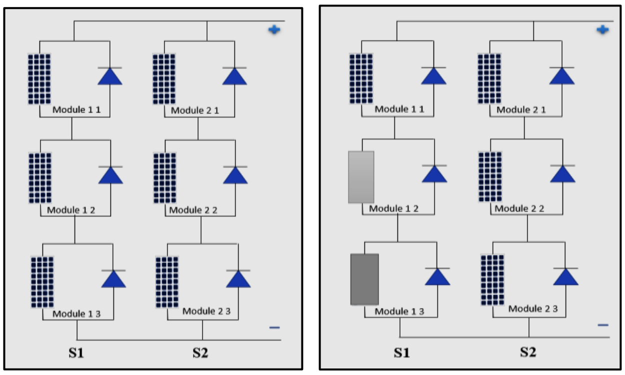
Case 1(1000 watts/m^2): All the modules in string S1 and S2 in the PV array is exposed to uniform irradiation of 1000 watts/m^2 at a 25^{0}C of temperature and is denoted diagrammatically by figure 9a.

(B) With conditions of partial shading

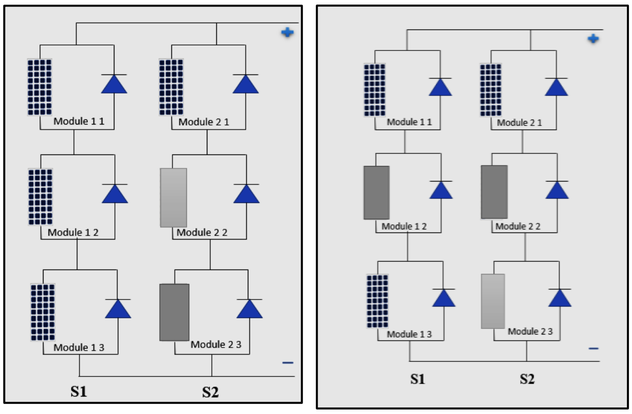
Case 2 (PS-S1): The PV modules M12 and M13 of first-string S1 are partially shaded with irradiation of 700 watts/m^2 and 400 watts/m^2 at a temperature 25^{0}C of respectively while the first Module M11 and the parallel string S2 are still received irradiation of 1000 watts/m^2 at a temperature of 25^{0}C and is denoted diagrammatically by figure 9b.

Case 3 (PS-S2): The PV modules M22 and M23 of first-string S2 are partially shaded with irradiation of 700 watts/m^2 and 400 watts/m^2 at a temperature 25^{0}C of respectively while the first Module M21 and the parallel string S1 are still receiving irradiation of 1000 Watts/m^2 at a temperature of 25^{0}C and is denoted diagrammatically by figure 9c.

Case 4 (PS-Random): Analysis of partial shading condition of PV array at miscellaneous shading with randomly selected shaded modules in both the strings with diverse solar irradiance over the PV Array. The randomly selected module M12 of the string S1 is subjected to the irradiance of 400 watts/m^2 and the modules M22 and M23 in string S2 are subjected to 400 watts/m^2 and700 watts/m^2 and is denoted diagrammatically by figure 9d.



(a) (b)



(c) (d)

Fig 9: Diagrammatic representation of PV array setup under study with different shading pattern. The dark gray color shows 700 watts/m^2 and light gray shows 400 watts/m^2 at same temperature of 25^{0}C.

4.1 Simulation findings and performance evaluation of photovoltaic arrays under diverse partial shadowing scenarios

One must possess fundamental software expertise about MATLAB/Simulink for analytical model analyse . The x and y coordinate of I-V characteristics represent open-circuit voltage (Voc) and short circuit current (Isc) respectively. The x and y coordinates of P-V characteristics the shows the voltage and the generated power respectively.

Figures 10 represent simulated results for case 1 and Figures 11, 12, and13 represent simulated results for case 2, case 3, and case 4 respectively. Observing the curves for case 1 in figure 10, as there is no shading condition and all the modules are subject with equal solar irradiations, the curves show their original shapes the curve obtained in I-V & P-V characteristics. Nonetheless, for cases 2, 3, and 4, as depicted the I-V & P-V curves shown in figures 11, 12, and 13, when PV modules along the string at different locations of the array are subjected to different levels of solar irradiation develop steps and peaks or notches indicating occurrence power losses in the PV system. Under these conditions, multiple local maxima are observed in the curves, among them there exhibit one global maximum point or peak point[64]. This section describes the implementation of the 3 × 2 series-parallel PV array configuration under two different scenarios of uniform irradiation and partial shading conditions of the PV modules and the output is measured by observing the changes in the I-V & P-V curves. The literature identifies that whatever be the partial shading pattern, the characteristic curve will always have local maxima equal to total series modules connected in a string which validates our results[65,66,54].

As seen in Figures 11, 12, and 13, showing shading patterns for Cases 2, 3, and 4, respectively, the number of peaks or steps and their magnitude are dependent on the irradiance level, shading pattern, and array arrangement, and temperature. The paper here focuses on the impact of two parameters the irradiation level and the shading location especially on series-parallel type of Array configuration[67].

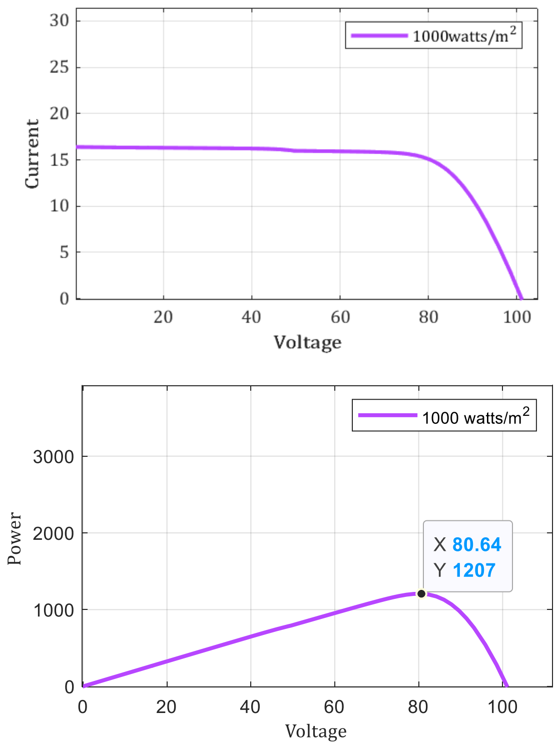
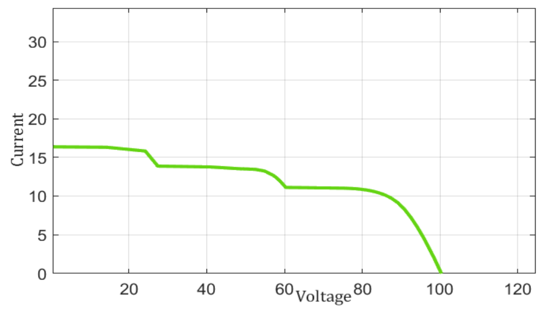


Fig. 10: The simulated results of case 1 under no shading



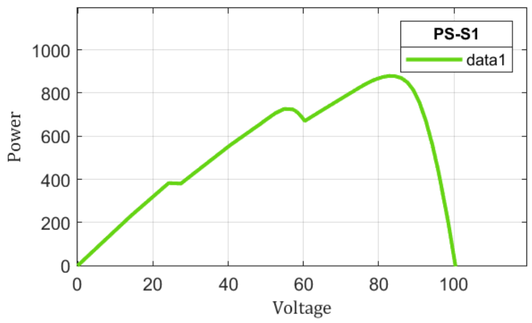


Fig. 11: The simulated results of case 2 shading pattern

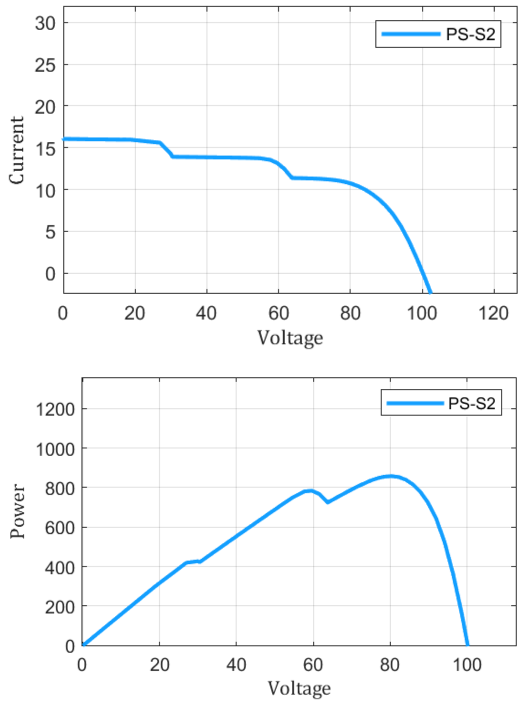
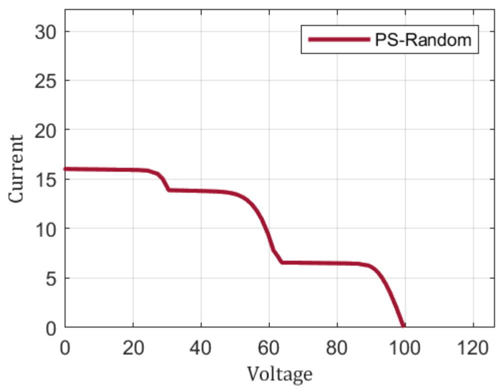


Fig. 12: The simulated results of case 3 shading pattern



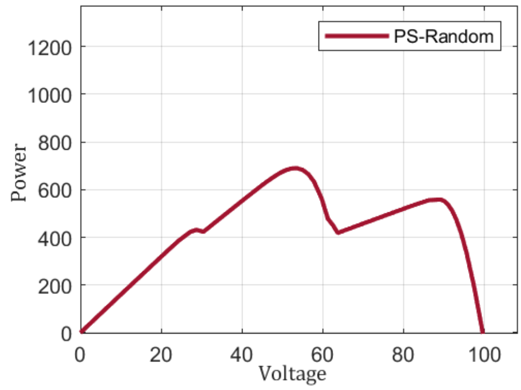


Fig. 13: The simulated results of case 4 shading pattern

The study in this paper presents the analytic technique to acquire knowledge that in what way partial shading affects PV array in assistance with literature. A lot of research paper have performed the work on MATLAB/ Simulink and showed a similar result as obtained in our paper. The results from research paper show a similar output where the output power is relational to the solar irradiance and the results were carried out through MATLAB /Simulink. The rate at which the output power reduces for different photovoltaic technologies depends on the change in solar irradiation[68].

Another recent research paper validated their hypothesis to predict local maxima is through simulation results wherein the authors displayed the occurrence of local maxima and global maxima in the I-V & P-V graphs[54]. Also, likewise our paper a lot of researchers make use of C/MATLAB to study analytical modelling implementation to understands the essentials of partial shading[69,70].

4.2 Interpretation of Mismatching power loss $\Delta P_{Loss}(\%)$

The I-V & P-V characteristics in figure 14 gives the comparison among the curves with respect with to magnitude and shape of the graph to facilitate knowledge of the impact partial shading at different locations of the PV module. The figure depicts the different outputs after diverse partial shading pattern under study and carefully examine and compare different output under shading and compare results in terms of shape and magnitude change. The I-V graph in figure 14a reveals that when a PV array when exposed to uniform solar irradiation and there is total absence of any type of shade, the characteristic curve has a usual shape with a single peak. However, the other three curves show a change in shape and magnitude than the usual I-V curve subjected to different partial shading. Multiple steps are introduced in the shape of the graph due to partial shading of different modules under different partial shading conditions. A slight drop is observed in the short circuit current from 16.4 amperes under uniform irradiation conditions and 16.37 amperes, 16.05 amperes, and 16.03 amperes for case 2, case 3, and case 4 respectively also in the open-circuit voltage drop from 101.1volts under uniform irradiation to 100.4 volts, 100.2 volts to 99.5 volts for case 2, 3 and 4 respectively.

Figure 14b demonstrates that the even P-V curves are also affected by partial shading by the existence of multiple notches with partial shading. Additionally, a decline in the maximum power generated is observed. Figure 14c depicts the data in the graphical form for the generated maximum power for each partial shading scenario. The maximum power delivered by the PV array in cases 1, 2, 3, and 4 as 1207 W, 879.1 W, 856.7 W, and 689.5 W, respectively is observed in figure 14c. Table 1 is the tabularized data of simulation results obtained from the P-V characteristic of figure 14c, which shows the maximum power generated and voltage at which maximum power is generated of all the simulation setups under consideration from figures 10-13.

Table 1. Maximum power generated under different shaded set-up

Uniform solar irradiance (watts/m²)	**Partial shading under study (watts/m²)**	**Pmax (Watt)**	**Vmax (Volt)**
1000	1000	1207	79.48
1000	PS-S1	879.1	83.52
1000	PS-S2	856.7	78.88
1000	PS-Random	689.5	55.64

The performance can be described by calculating mismatching power loss $\Delta P_{Loss}(\%)$ under various shading case1, case 2, case 3, and case 4[71,72]. The equation 4 gives the mismatching power loss $\Delta P_{Loss}(\%)$ as follows

$$\Delta P_{Loss}(\%) = \frac{P_{MUI}-P_{MPS}}{P_{MUI}} \times 100 \qquad (4)$$

Where, P_{MUI} maximum generated power under uniform irradiation and P_{MPS} maximum power generated under conditions of partial shading. In case 1, shown in the characteristic curves in figure 14a and figur14b both the curves show actual characteristics under no shading and uniform irradiance of 1000watts/m². The generated maximum power is 1207 watts as shown in figure 14c. Analyzing case 2, with two PV modules in string S1 partially shaded with different solar irradiance levels keeping string S2 at uniform irradiation, there is a slight drop in open-circuit voltage and short circuit current and the maximum power generated reported is 879.1 Watts.

The mismatching power loss $\Delta P_{Loss}(\%)$ under this condition is 27.16%. In case 3 when the two PV modules of string S2 are partially shaded with two different solar irradiances keeping string S1 at uniform irradiation, then a similar pattern as in case 2 in the I-V & P-V Curves is seen.

In case 2 and 3, the curves deviated from their normal pattern. Due to the connected bypass diode along each module, the I-V characteristics exhibit multiple steps, and the P-V characteristics exhibit multiple peaks or notches. The maximum power generated is 856.7 watts under the shading pattern in case 3. The mismatching power loss $\Delta P_{Loss}(\%)$ in case 3 is calculated to be 29 %.

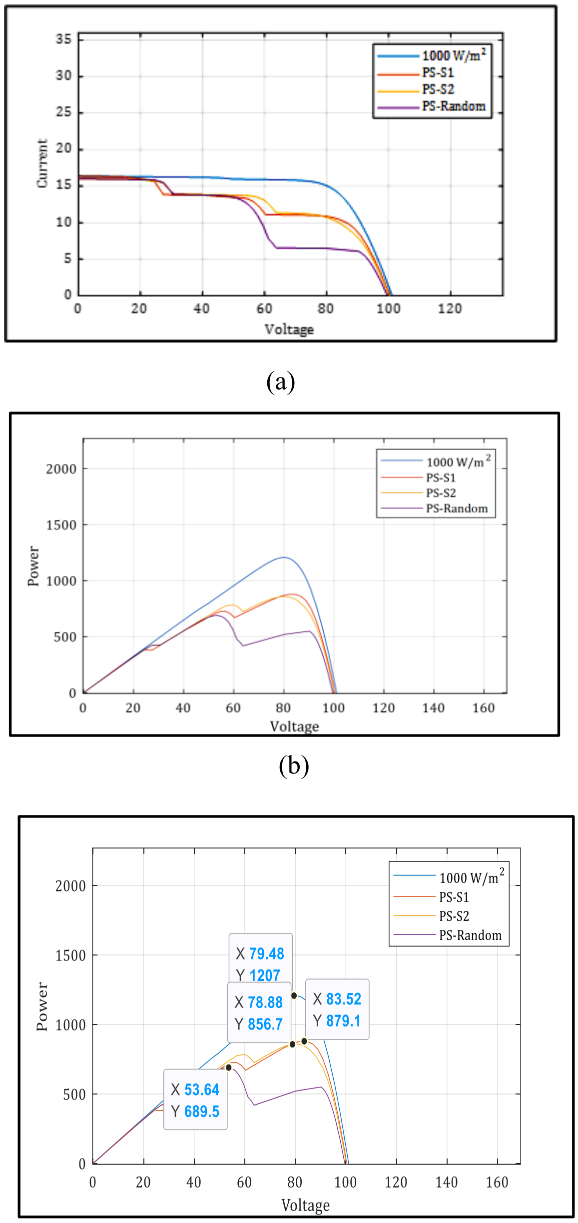


Fig.14: Comparative results of different partial shading conditions (a) I-V characteristics for cases 1, 2, 3, and 4 (b) P-V characteristics for cases 1, 2, 3, and 4. (c) P-V characteristics with maximum power generated for cases 1, 2, 3, and 4

In case 4, the characteristic curves show a significant variation than in case 2 and case 3. A very prominent decrease in short circuit current and open-circuit voltage can be seen in the comparison I-V graph represent in figure 14a. The maximum generated power is 689.5 watts under the shading pattern of case 4. The mismatching power loss $\Delta P_{Loss}(\%)$ in case 4 is calculated to be 42.8%.

Over last decade one of the prominent reasons identified for the degradation of the solar photovoltaic panels is formation of hotspots. There many reasons for the hotspot development, one of them is shadowing which causes localized heating panel leading to complete damaging under severe conditions.

1. The presented paper would help the academician, researchers and even manufacturers to acquire some insightful information as how shadowing a panel would impact the various electrical parameters performance associated with solar PV module.
2. The researcher and manufacturer could study the severity of the situation of panel under shadow and more work can be done on how the PV modules can protected under shaded conditions.

5. Conclusion

The presented research paper fundamentally concentrates to understand the consequences of shading when PV modules are shaded. The model under study is a 3*2 PV array setup while the outcomes are executed through simulation in MATLAB/ Simulink. The two important electrical characteristic curves of a PV array are being analyzed. The results after simulation demonstrated that the shape of the I-V & P-V curve of shaded modules diverged significantly from the actual shape of the graph obtained in the absence of shading. The curves show multiple-step and notches which are a clear indication of stimulation of bypass diode. Also, simulated results display drop in the generated power due to influence of variation in solar irradiance. The simulation result show that shaded PV modules with bypass diode connected are highly influenced by shading locations subjected to the PV array. Larger the number of shadings, more alterations in the output of PV arrays. The last part of paper mathematically estimates the mismatching power loss (ΔP) Loss(%) under partial shading conditions. The distinguished power losses obtained are 27.16%, 29%, and 42.8% for partial shading pattern cases 2, 3, and 4, respectively. Finally, it can be summarized that shading has the potential to cause PV module degradation and various losses. Using MATLAB /Simulation, our future research will investigate the effect of shading on different photovoltaics.

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