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Effect of Non-uniformity of Irradiance on the Performance of Solar PV Array using MATLAB/Simulink

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Abstract

To meet the growing demand of energy due to socio-economic growth and industrialization, there is a gradual increment in the use of renewable energy resources. Among the renewable energy, power production from solar PV system is dominating to other resources due to clean, greener and easier energy production process.Because of direct conversion of solar energy into electricity without any moving or rotating parts, solar power generation is become the most favourable and effective technology. But the solar photovoltaic system power output is environment dependent i.e.,the power output from solar PV system depends on the solar irradiance, temperature, humidity, geographic location etc. The most prominent factor that affects the power output is solar irradiance. The solar radiation received by the surface of solar PV module is affected by moving cloud, nearby building, leaf falling from tree, dust etc which is called shading on the system. In this thesis, the reference system of 6.72 kW is simulated under various shading condition using MATLAB/Simulink to analyse the performance of solar PV array.

The result of this study shows that, the performance parameters of solar PV array are greatly impacted by the change in irradiance level by the surface of solar PV module. Under partial shading condition, the P-V characteristics of solar PV array exhibits multiple peaks in characteristics curve in which the smaller peak are called local maxima and the highest one is called global maximum power point. Under the defined conditions of shading, when the irradiance level is reduced to 50% from STC, the traditional solar PV array configuration i.e. series-parallel configuration, power output is reduced almost by 48% that of STC conditions. By changing the configuration type into bridge-linked and total cross-tied configuration, the performance of solar PV array somehow can be improved. The simulation result shows that, under defined shading conditions when irradiance level is reduced to 50% from STC, the total cross-tied (TCT) configuration produces 4.75% and 2.21% more power output than series-parallel (SP) and bridge-lonked (BL) respectively. Other parameters fill factor and shading loss also improves with the total cross-tied configuration under shading conditions. The Monte Carlo simulations for various shading scenarios showed that the shading scenarios have similar impact on the output of PV array.It was found that, for the system under study under shading conditions, a power output of 3360 watt have maximum probability of occurrence of 16%.

Keywords

Solar photovoltaic array configuration, Irradiance Level, Shading, Maximum power, Fill factor

1. Introduction

Energy resources that produce electrical energy can be broadly classified into two categories: renewable and non-renewable sources of energy.The main disadvantage of non-renewable energy is that its sources may deplete and it has adverse impact on the environment, which makes people shift towards the use of clean and green renewable energy technology.The increasing global concern, for the environment has led to a surge in interest in energy technologies, driven by agreements and commitments to reduce harmful emissions such as carbon.

External varying conditions such as solar irradiance, temperature, humidity, cloud etc. has great impact on the output from solar panel. Solar energy harvesting is inconsistent in nature as it depends on the weather condition such as temperature, wind, cloud movement etc. External conditions cause hindrance to the path of sunlight and hence produce complex characteristics[1]. The most typical external environment conditions that impact the performance of a solar PV panel are total or partial shadowing of the panel surface, fluctuating temperature, and the amount of solar radiation. When it comes to solar energy, the most typical issue is complete or partial shade. Since PV technology has been around for a while, the effect of partial or total shade has had a significant impact on the optimal performance of Solar PV panels[2]. Along with reduction on the output of the solar PV module, partial shading also causes long-term degradation of the module. Under the uniform irradiance level, the output characteristics curve exhibits a single peak but when partial shading occurs P-V curve have multiple peaks due to use of bypass diode[3].To acquire the desired level of power output, several solar PV modules are arranged in the series and parallel connection. The series connection of PV module increases the voltage level while the parallel connection increases the value of current. There was various connection configuration of solar PV array,among them three different configurations namely series-parallel, bridge-linked, and total cross-tied configuration for 3*3 solar PV array is shown in Figure 4 - Figure 6. Series-parallel connection is the well-known array configuration in which modules are connected firstly in series string and these strings are then connected in parallel. The bridge-linked configuration is formed with four solar modules in which two modules are connected in series and then are connected in parallel to form bridge structure through cross ties[4].

Shading on the solar panel may occur due to the passing of clouds, dust deposited on the surface of the panel, leaf falling on it, shades of trees, neighbouring buildings and module, poles etc. Shading are of two types: uniform shading and non-uniform/partial shading depending upon the shading objects.Two types of partial shading occur in the PV module: dynamic and static shading. In dynamic shading, shadow move over the PV module such as cloud moving and in static shading the shadow stays on the module for a time[5].

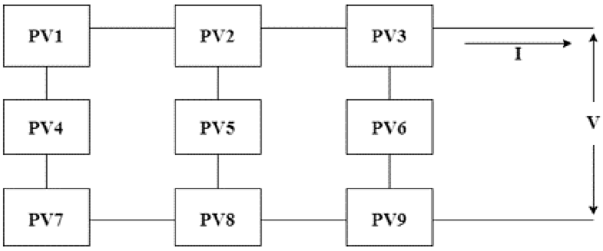

Figure 1: Series-parallel configuration

Under uniform shading, all the solar cells/modules receive the same amount of solar irradiance, and there is single maximum power point in the I-V and P-V characteristics. Partial shading on the solar PV panel is a serious issue because: i) the power loss within the individual shaded cell results in local heating, thereby increasing the cell temperature and creating thermal stress on the whole module, causing hotspots that can lead to the failure of the entire PV panel, ii) under extreme cases of shading ,the reverse bias on the photovoltaic cell might exceed its breakdown voltage, leading to development of cracks and a short circuit occur at the serial branch where the cell is connected[6][7].

The bypass diode connected across selected cell/module helps in overcoming the problem of hotspots. Under partial Shading conditions, use of bypass diode causes the current from unshaded modules to the short circuit created by diode, but it also results in the presence of multiple peaks on the characteristics curve[8].

The main objective is to carry out the analysis of effect of static partial shading (non -uniformity of irradiance) conditions on the performance of a solar PV array using MATLAB/Simulink and to compare the performance parameter such as maximum power output, fill factor and mismatch power loss under defined shading conditions for different array configurations with varying the solar irradiance level. And at the end, studying the impact of various shading scenarios on the power output of solar photovoltaic array through Monte Carlo simulation. Monte Carlo (MC) simulation is a computational technique used to estimate the outcomes of complex systems or processes through random sampling and statistical analysis. MC simulation can be used in various fields such as engineering, online gaming, business, and finance[9].The python programming language is used in this research to perform the MC simulation.

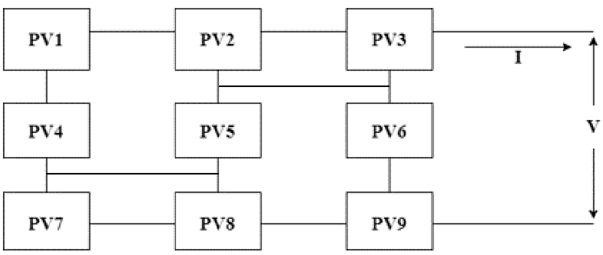

Figure 2: Bridge-linked configuration

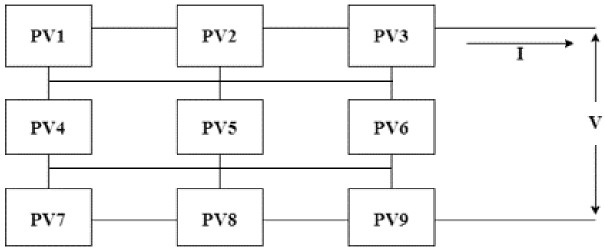

Figure 3: Total cross-tied configuration

2. Methodology

2.1 Data collection of reference solar PV array

For the study, the solar PV array installed at ICTC building, Pulchowk Campus is taken as a reference system. The array consists of three strings, each containing eight solar modules of 280 Wp, 24 V each in series. The detailed parameters of the module under STC and details of the solar PV array are presented in the Table 1 and Table 2 [10].

Table 1: Parameter of PV module 280P-24

Parameter	Value
Maximum power (Pm),W	280
Voltage at maximum power (Vm),V	36.3
Current at maximum power (Im), A	7.72
Open circuit voltage (Voc),V	44,3
Short circuit current (Isc), A	8.36
Total numbers of series connected cell (Ns)	72
Short circuit current temperature coefficient (Ki)	0.06%/oC
Module efficiency	14.39%
Power tolerance	+/- 3%
Module area	46.3 m^2

Table 2: Details of reference PV array system

Array	3 nos. of string 8 nos. of 280W LDK panel
PV combiner box	1 no. of box with 3 nos. of 16A DC breaker
Solar charge controller	1 no. of 240 V
Battery bank	20 nos. 12V/200AH: all in series to form 240V bank (EXIDE)
Online UPS	1 no. of 176-300V/ 10 kWac

2.2 Mathematical modelling of solar PV cell/module

In this research Rp-model known as single diode model is used because of its wide application areas and simpler to illustrate. The equivalent electrical circuit of Rp-model is shown in Figure 4 [11].

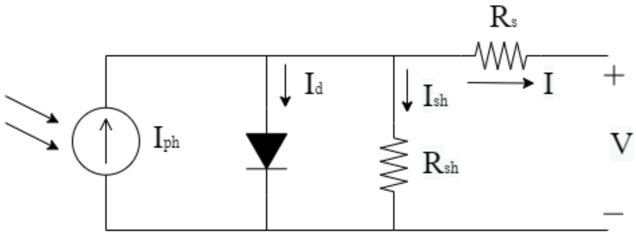

Figure 4: Equivalent circuit of one-diode model solar cell

The characteristics equation that describes the equivalent circuit of a solar cell was describe in the following equation [11][12][13].

$$I = I_{ph} - I_d - I_{sh} \tag{1}$$

$$I = I_{ph} - I_s \left\{ exp^{\frac{q(V+IR_s)}{nKT}} - 1 \right\} - I_{sh} \tag{2}$$

Where, I_{ph} = Photocurrent (A)
$I_d = I_s\{e^{\{}q(V + R_s I)/nKT\} - 1\}$,called diode current
I_s = Diode saturation current (A)
I_{s_h} = Current through shunt resistor (A)
q= Electronic charge (1.6021 * 10^{-23} C)
R_s = Series resistance, ohm
n = Diode ideality factor which varies in range between 1-2 for silicon cell
K = Boltzmann constant (1.38 * 10^{-23} J/K)
T = Solar Cell working temperature (K)

$$I_{ph} = \frac{[I_{sc} + K_i(T - T_{ref})]}{1000} G \tag{3}$$

Where, I_{sc} = Short circuit current of solar cell (A)
K_i = Solar cell's short circuit current temperature coefficient
T_{ref} = Reference temperature at STC = 25 oC
G = Irradiance on the surface of solar cell W/m^2

$$I_s = I_{r_s} \left(\frac{T}{T_{ref}} \right)^3 e^{\left\{ \frac{qE_g}{nK} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right\}} \tag{4}$$

Where, E_g = Band gap energy of semiconductor I_{r_s} = reverse saturation current and is given by

$$I_{r_s} = \frac{I_{sc}}{e^{\left(\frac{V_{oc}}{nV_t} \right)} - 1} \tag{5}$$

Where, V_{o_c} = open circuit voltage of cell and is given by

$$V_{o_c} = \frac{KT}{q} \tag{6}$$

The current through shunt resistor is given by equation

$$I_{s_h} = \frac{V + IR_s}{R_{s_h}} \tag{7}$$

There have been various methods proposed by the researchers to determine the value of shunt and series resistor. Among them, the simpler method described by [14] is applied in this thesis, which states that:

$$R_{s_h} > 10 \frac{V_{o_c}}{I_{sc}} \qquad R_s < 0.1 \frac{V_{o_c}}{I_{sc}} \tag{8}$$

$$I = N_p I_{p_h} - N_p I_s \left\{ e^{\frac{q}{nKT}\left(\frac{V}{N_s} - \frac{IR_s}{N_p} \right)} - 1 \right\} - \frac{\frac{N_p V}{N_s} + IR_s}{R_{s_h}} \tag{9}$$

To get a sufficient amount of power and voltage at the output, numerous solar cells are connected in series and parallel to form a solar PV module. As a result, the equivalent circuit of a solar PV module has N_s number of series cells and N_p number of parallel cells. The relation between the output current and voltage of the PV module is given by the equation 9.

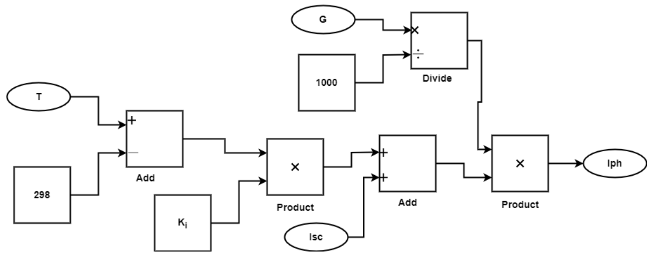

Figure 5: Modelling of Photo-current

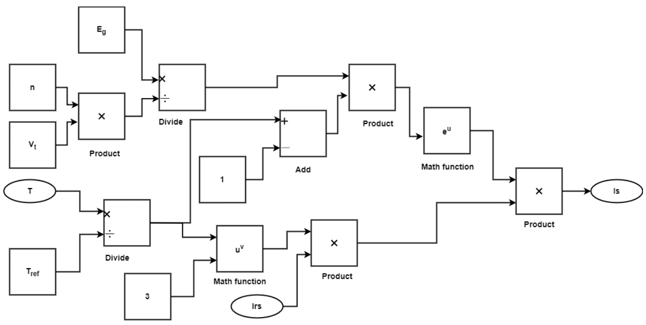

Figure 6: Modelling of diode saturation current

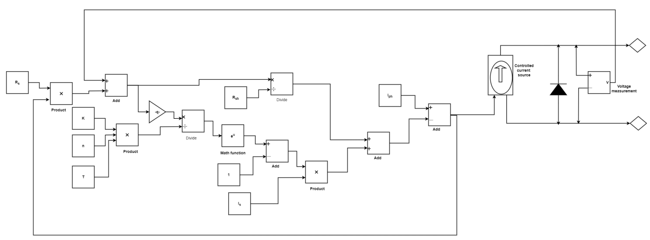

Figure 7: Modelling of PV module output current

2.3 Modelling of reference solar PV array system on MATLAB/Simulink

Using equation (1) to (9), a solar PV module is built on the Simulink as shown in Figure 5 - Figure 8. Since array is a series and parallel connection of solar PV modules, the reference solar PV array (3*8) system is used for simulation. The irradiance is fed as an input signal to the solar PV module block, along with the open circuit voltage and short circuit current. By varying the value of the irradiation given to the solar module, different shading strategies can be formulated. Solar cells/ solar panels in the simulation are subjected to a different shading strategies by varying the magnitude of the signal in the signal builder block connected to each set.

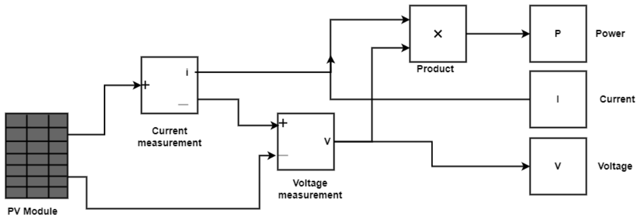

Figure 8: Final model of reference PV module

2.4 Shading strategy

To study the performance of reference system of the 3*8 solar PV array configuration, different shading cases, where irradiance level of twelve module of the array changes from 10% to 90% , were defined, as shown in Figure 9. The irradiation values used in simulation for study are: 1000 W/m^2, 900 W/m^2, 800 W/m^2, 700 W/m^2, 600 W/m^2, 500 W/m^2, 400 W/m^2, 300 W/m^2, 200 W/m^2 and 100 W/m^2. For each condition of shading, the I-V and P-V characteristics curves are obtained by keeping constant temperature at 25 °C.

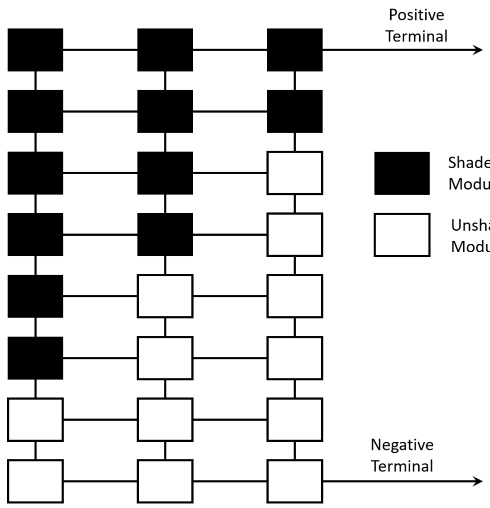

Figure 9: Shading scenario on reference PV array

3. Result and Discussion

3.1 Validation of MATLAB/Simulink Model of solar PV module

To validate whether the Simulink module provides accurate results or not, an experiment was carried out on a SW020P model, 20 Wp polycrystalline PV module. A PV module, variable resistor, pyranometer and multimeters were used for the experiment. A 10 ˙ variable resistor was connected across the PV module, and under varying irradiance conditions, the power output from the PV module was measured. The output from the experiment was compared with the output result from the simulation under similar conditions of experiment and the result were tabulated in the Table 3.

Table 3: Comparative result of model validation

Irradiance (W/m^2)	Experimental Output (W)	Simulation Output (W)	Difference (W)
780	9.56	10.09	0.53
740	7.03	7.63	0.60
540	4.63	4.99	0.36
320	2.31	2.1	0.21
120	0.21	0.23	0.02

It has been found that there is slight difference between the experimental and simulation results, which might occur due to instrumental error. This indicates that the Simulink module can be used for the further study on the array.

3.2 Simulation of reference module under shading condition

The I-V and PV characteristics curve of a module under different irradiation values is shown in Figure 10. From the curve, when the value of irradiation goes on reducing, the short circuit current and open circuit voltage of the PV module decrease. Additionally, the maximum power output also decreases along with the irradiance level because of which the MPP on the P-V curve shift towards the left i.e., the voltage at maximum power reduces, and so does the current at maximum power.

From the I-V characteristics curve, for the same value of voltage, the current is less with a reduction in irradiance level received by the PV module. So, from Ohm's law, for the fixed value of voltage, the current is reducing, which means the value of resistance is increases. This indicates that when the irradiance level was reducing, the value of module resistance increases. When the irradiance level is varying from 1000 W/m^2 to 100 W/m^2, the voltage is slightly affected, but the current reduces proportionally with the irradiance level, and hence, the power output from the module reduced.

3.3 Simulation of series-parallel solar PV array configuration under shading condition

Under STC, all the module on the PV array is subjected to equal amount of irradiance of 1000 W/m^2 at 25°C. The characteristics of the PV array under this condition generate a maximum power of 6708 W with single MPP, as shown in Figure 11. The simulation results show that the changes in the shading condition affect the performance of the reference array. Under uniform shading, there is an equal distribution of solar irradiance within the modules of the array, and hence, no mismatch between the modules. But under non-uniform shading cases, the mismatch causes multiple peaks on the P-V curve. The multiple peaks on P-V curves are due to varying irradiance levels and interactions between shaded and unshaded modules. Because the short-circuit current of a PV cell is proportionally affected by the level of irradiance, the non-uniformity of irradiance results in a decrease in photo-current for the shaded PV modules, while the unshaded modules continue to function at a greater photo-current. The shaded modules operate in the reverse bias zone to carry the greater current of the unshaded modules since the string current must be the same through all series-connected modules. Because of the reverse voltage polarity, the shaded modules drain electricity. As a result, the maximum extractable power from the shaded PV array falls.

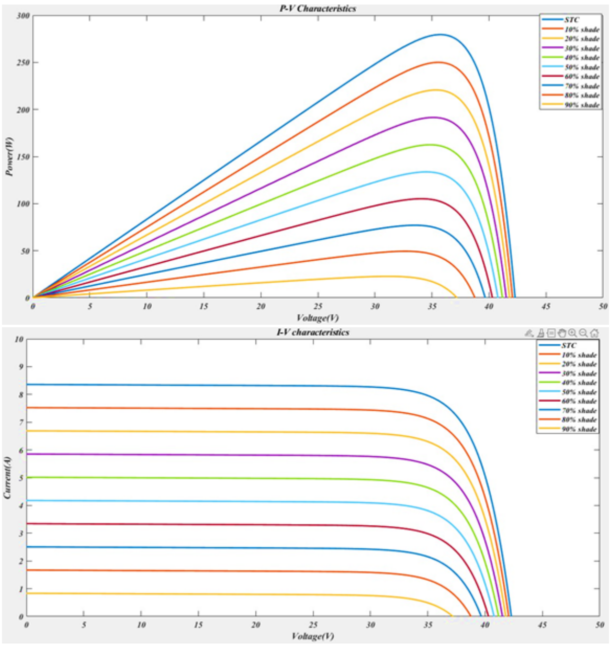

Figure 10: P-V and I-V characteristics of reference module under uniform shading

3.4 Simulation of reference array by changing the configuration into Bridge-Linked (BL) and Total-Cross-Ties (TCT) type

The module connection of the original reference array was changed into BL and TCT type configurations, and the modified array was then simulated under the different cases of the irradiance level. The results of this simulation will help to investigate how the changes in array connections affect the performance behaviour of the solar PV array under shading conditions.

3.4.1 Simulation of BL solar PV array configuration

The reference SP array configuration was changed into BL type configuration by introducing some additional cross-connection in bridge rectifier fashion within four modules, and simulation was carried out. Under defined conditions of shading, the irradiance received by the shaded module is varied as 1000 W/m^2 (STC), 900 W/m^2 (10% shade), 800 W/m^2 (20% shade), 700 W/m^2 (30% shade), 600 W/m^2 (40% shade), 500 W/m^2 (50% shade), 400 W/m^2 (60% shade), 300 W/m^2 (70% shade), 200 W/m^2 (80% shade) and 100 W/m^2 (90% shade), and the characteristic curves are plotted, as shown in Figure 12.From the Figure 12 , under the same irradiation on the all modules there is a single peak point on the P-V characteristics curve. However, when there in non-uniform irradiance level given to the shaded and unshaded module, the array exhibits multiple peak points on the curve due to mismatch of irradiance between the solar PV modules within the array.

3.4.2 Simulation of TCT solar PV array configuration

The original SP array configuration was transformed into a TCT configuration by adding cross-connections within each row. These cross-connections are designed so that the total current meeting at each connection point is equal, and the voltage across each connection point is also equal. Following this modification, a simulation is conducted.

During this simulation, specific shading conditions were defined, where the irradiance (amount of sunlight) received by the shaded module varies systematically. This variation ranges from 1000 W/m2 under standard test conditions (STC) to as low as 100 W/m2 with 90% shading. The simulation generates a characteristic curve, as shown in Figure 13, which represents the relationship between current and voltage (P-V characteristics).

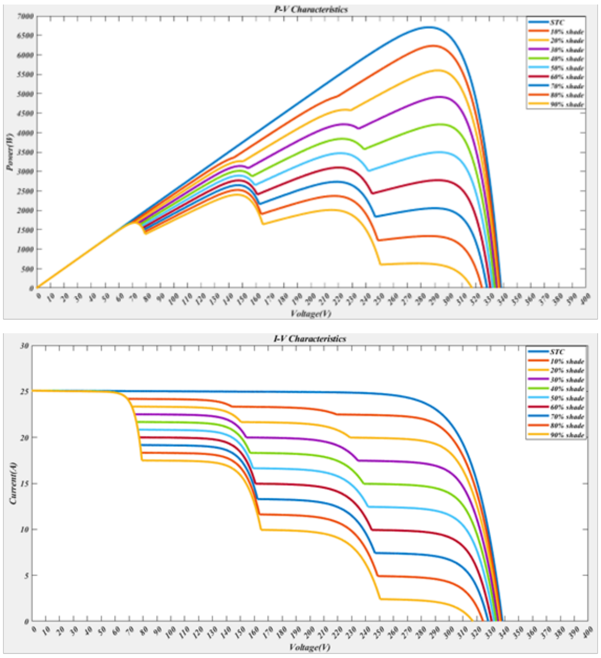

Figure 11: P-V and I-V characteristics of reference array under shading

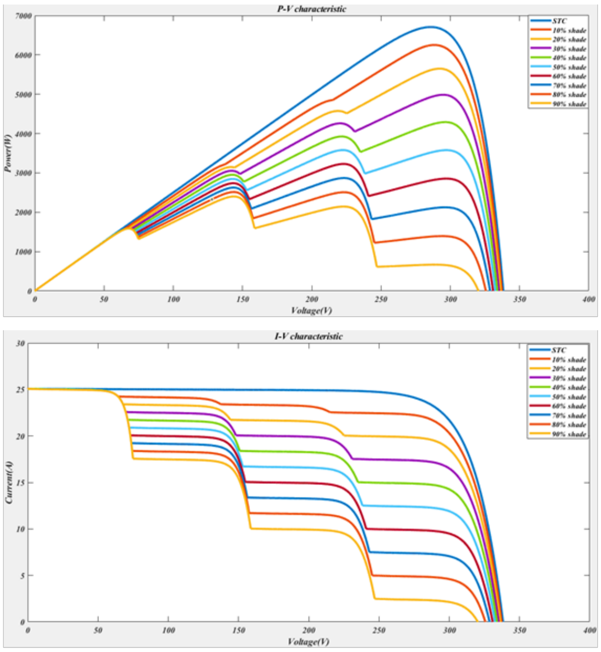

Figure 12: P-V and I-V characteristics of BL array under shading

The results depicted in the curve are notable: when the entire module receives uniform irradiation, there is only one peak point on the P-V curve. However, when non-uniform irradiance levels are applied, with some modules in the shade and others in full sunlight, the curve displays multiple peak points. These additional peaks are a consequence of the uneven distribution of sunlight across the array.

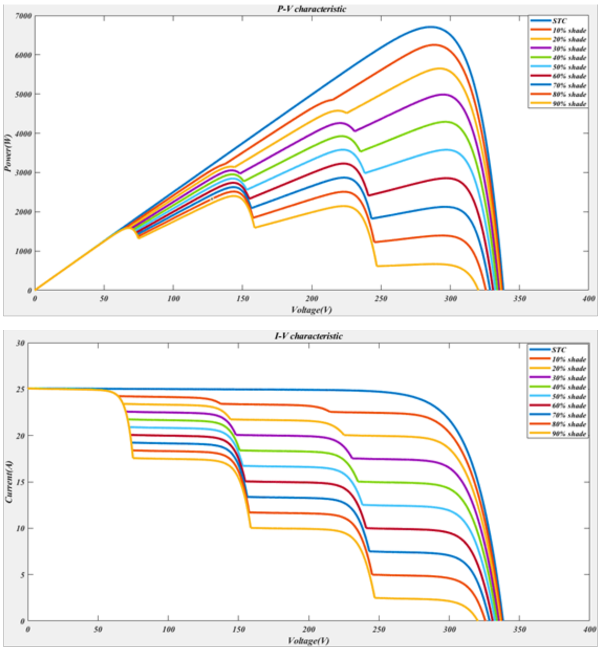

Figure 13: P-V and I-V characteristics of TCT array under shading

3.5 Comparison of the performance of BL and TCT arrays with SP connection of PV array

The simulation evaluates and discusses the PV array performance parameters, such as maximum power output, fill factor (FF), and mismatch loss for every case of shading/irradiance for each array connection.

3.5.1 Maximum Power

Under non-uniformity of the irradiance, all three-array configuration have multiple peaks in the characteristics curve, in which the highest peak is called the global maximum power point (GMPP) and others are called local maximum power points. The GMPP usually represents the maximum extractable power from the array under the conditions of the given irradiance level and the temperature conditions.

From Table 4, it is seen that the TCT array configuration has a higher maximum power output in almost all cases of non-uniformity of irradiance compared to BL and SP configuration, which is basically the additional loop provided by the TCT configuration to flow the current under mismatch conditions.

3.5.2 Fill Factor

Fill factor (FF) is the ratio of actual maximum obtainable power to the product of short circuit current (I_{sc}) and open circuit voltage (V_{oc}).The performance of the solar PV array is said to be better, if fill factor is close to unity.

$$FF = \frac{P_{mpp}}{I_{sc}V_{oc}} \tag{10}$$

Table 4: Maximum power output from SP, BL and TCT array

Shading	Global Maximum Power, Pm (W)		
	Series-Parallel	Bridge-linked	Total-cross-ties
STC	6708	6708	6708
10% shade	6231	6251	6269
20% shade	5599	5650	5697
30% shade	4915	4986	5053
40% shade	4210	4291	4360
50% shade	3494	3581	3660
60% shade	3100	3228	3222
70% shade	2733	2870	2871
80% shade	2524	2515	2525
90% shade	2401	2401	2414

Table 5: Fill Factor under shading

Shading	Fill Factor		
	Series-Parallel	Bridge-Linked	Total-Cross-Tied
STC	0.791	0.791	0.791
10% shade	0.737	0.740	0.742
20% shade	0.664	0.670	0.676
30% shade	0.585	0.594	0.602
40% shade	0.503	0.513	0.521
50% shade	0.419	0.430	0.439
60% shade	0.374	0.389	0.388
70% shade	0.332	0.349	0.348
80% shade	0.310	0.296	0.309
90% shade	0.302	0.299	0.301

Under shading condition, there is only slightly change in open circuit voltage and almost an equal short circuit current in each case of shading. This is because the open circuit voltage is primarily determined by band-gap energy of the semiconductor material used in the solar cells. Shading doesn't drastically alter the band-gap energy, so the voltage across the cell remains relatively constant. Additionally, temperature also affects the open circuit voltage, but here we assume a constant temperature for all cases. Moreover, when a solar cell is shaded, the shaded area effectively acts as a resistor, limiting the current flow, but because solar cells generally have low internal resistance, the effect of shading on the short circuit current is relatively small.

Fill factor for all the configurations under different shading cases has been tabulated in Table 5. Under STC, SP, BL and TCT configurations , the fill factor values are the same, while for most other cases, TCT has a higher FF value than BL and SP configurations. With an increase in the shade amount, the fill factor decreases because of a reduction in maximum extractable power.

3.5.3 Mismatch power loss

Mismatch power loss(ML) is the difference between maximum power of PV array under STC and the maximum power of the array under mismatch/shading condition.

ML= $P_{(m,STC)}$ - $P_{(m,mismatch)}$

From Figure 14, it is seen that the power losses are higher for the SP configuration, followed by BL and TCT configurations. This implies that the TCT configuration performs better compared to other configurations under the defined conditions of shading with non-uniformity of irradiance levels.

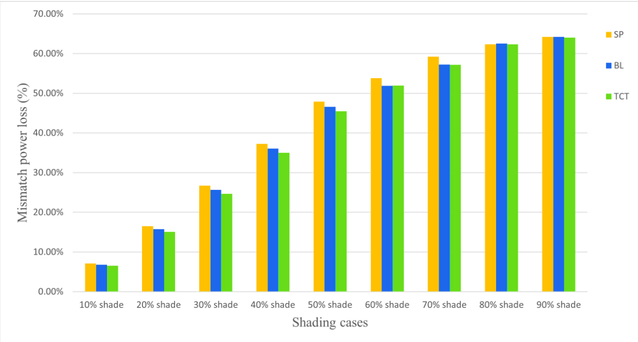

Figure 14: Mismatch power loss under shading

3.6 Monte Carlo Simulation

Using Python programming language, Monte Carlo simulation for the reference array system is performed. For each shading scenario, a set of output powers is obtained. Multiple simulation runs have been performed, and output powers are collected. A probability distribution curve is plotted for the values of the output power, shown in Figure 15 In the plot, the x-axis represents the power output in watts, and y-axis represents the probability (normalized frequency) for each power output value. A symmetrical bell-shaped curve is found from the simulation run, which indicates a normal probability distribution. This implies that various shading scenarios have a similar impact on the power output. The peak of the probability distribution curve i.e., 3360W, is the most probable power output having probability of occurrence 0.16, which also represents the mean power output under shading conditions.

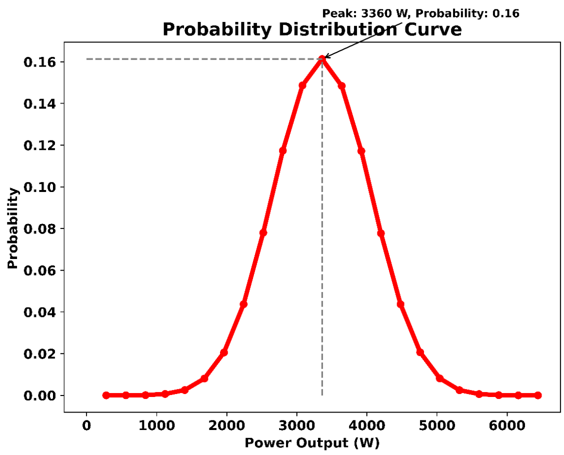

Figure 15: Probability distribution curve

4. Conclusion

The results of the simulations show that non-uniform irradiance distribution can lead to notable reductions in the overall performance of the PV array. Variations in irradiance levels across the array surface results in uneven current and voltage outputs from individual PV modules, causing power losses. It has been shown that the total cross-tied and bridge-linked configurations exihibit superior behaviour in terms of output power, fill factor and mismatch power loss compared to the series-parallel configuration. Under non-uniform shading, when the level of irradiance gradually reduces, the maximum power output decreases accordingly and it has been found that, at 50% of solar irradiance the maximum extractable output from the series-parallel configuration is only 3494W, which is 52.08% of STC. The effect of shading has been investigated on bridge-linked and total cross-tied configuration, the results showed that these configurations also have multiple peaks under non-uniformity of irradiance, and the maximum power output is 3581W and 3660W at 50% of solar irradiance respectively which is 53.38% and 54.56% of STC. Under the same shading conditions (50% irradiance), total cross-tied produces 4.75% and 2.21% than series-parallel and bridge-linked, respectively. Also, total cross-tied has lower mismatch loss of 45.45% than bridge-linked (46.62%) and series-parallel (47.91%), and a higher fill factor (total cross-tied=0.439, bridge-linked=0.430, and series-parallel=0.419).

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