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Theoretical and experimental analysis of photovoltaic module characteristics under different partial shading conditions

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Article Info	ABSTRACT
	Recently, the renewable energy resources have gained more attention in the electricity sector as promising technology to tackle the depletion in the traditional energy resources. Solar energy grows rapidly due to its vast applications. The performance of Photovoltaic (PV) system is affected by partial shading that results from building, clouds, and fallen leaves. This paper investigates theoretically and experimentally the impacts of various cases of partial shading; such as vertical string, horizontal string, and single cell at environmental conditions on the current-voltage and power-voltage characteristics of 88 W PV panel. In addition, diagonal shading with multi steps is considered in the analysis. The experiments are conducted with considering various parameters; such as shading position and ratio to validate the simulated results. The results show that at 100% shading condition, the maximum power drops by 99.36 %, 43.7%, and 41.15% for horizontal, cellular and vertical shading at the same solar radiation level comparing with their initial state value. Horizontal string shaded has the highest negative impact on the power and efficiency among other types of shadings. The comparison between the theoretical and experimental results reveals considerable agreement between the theoretical and experimental results.

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NOMENCLATURE

PV	Photovoltaic
I	current (A)
Iph	photon current (A)
Irs	reverse saturation current of diode (A)
V	voltage (V)
Rs	series resistance of PV cell (Ω)
A	ideality factor
VT	junction thermal voltage
Ns	number of cell in series
K	Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K)
Tc	cell temperature (°C)
Q	electron charge ($1.6021765 \times 10^{-19}$ C)

Fs   shading factor
Gt,s   shaded surface irradiances (W/m^2)
Gt   unshaded surface irradiances (W/m^2)
SA   shading area
Imax   current at the maximum power point (A)
Vmax   voltage at the maximum power point (V)
Pmax   power at the maximum power point (W)
ΔP   power loss of PV panel (W)
F.F   fill factor

1.   INTRODUCTION

The emission of carbon from the traditional electrical power generation technology is one of the most important reasons that lead to employ the renewable energy as alternative sources of electrical power generation. Solar energy is the best choice for electricity generation [1] because it is clean [2], cheap [3], silent [4], abundant and environmentally friendly energy resources [5].

Among different forms of renewable energy, PV represents one of the most promising renewable energy in the world [6, 7] due to its great advantages; such as zero emission of greenhouse gases, low maintenance cost, not rotating or moving parts [8, 9]. A PV cell is basically a semiconductor diode with a large barrier layer exposed to light allowing portion of the energy in the light photons arriving at the cell convert directly to DC electrical power [10]. The most notable factors that have a clear impact on the performance of PV system are: Partial shading, dust [5], sand [11], temperature [12], and solar radiation [13]. Partial shading is the most common encountered problem in a PV system. In this phenomenon, the received sunlight is reduced significantly and results in lower system efficiency [14]. In the design stage, the shadow of nearby objects avoided as possible. However, parts of PV module face unexpected shadows; such a sun melted snow, bird dung, fallen leaves, the neighboring buildings, towers, and passing clouds [15, 16]. When the PV module partially shaded, the shaded cell operates at current levels lower than unshaded cell. As consequence, the shaded cells are forced into reverse bias and begin consuming power instead of generation power. This lead to undesired increase in cell temperature this is lead to localized overheating (hot spot). When this temperature reaches the critical limit, the effected cell (shaded cell) can be damaged [17]. Passive and active methods are used for decreasing the power losses which are caused by partial shading. In the first method, the bypass diode is connected in antiparallel with the photovoltaic cells in order to pass the current and avoid the destructive impact of shading. Current flow in the diode causes losses in power, therefore, it is not possible to avoid losses completely. On the other hand, the dynamic reconfigurations between the panels of photovoltaic represent second method (active method) [18, 19]. H. H. Khaing et al [20]: Studied the effect of different partial shading on four various types of PV modules that involve amorphous thin-film, CIGS thin-film, CdTe thin-film and multi-crystalline PV modules. The module tested along the length side and along the breadth side with different shading rate varied from 10% to 60% from the PV area with increase of 10%. The result showed that shading along the breadth side more effected than shading along it's length side. G. S. Reddy et al. [21] Presented PV module model by MATLAB/ Simulink to analyze their performance under nonuniform irradiance condition. Moreover, Various PV array simulation schematic could be created by the proposed model, and parameters of irradiance of each PV module can be set independently. Different simulation process is conducted and compared for different array configurations (2 series, 3 series, 2series × 2parallel and 3 series × 2 parallel) under nonuniform irradiance conditions of I-V and P-V characteristics curves. M. Abdullah et al [22], investigated the impact of shading on the effectiveness of PV panel. The experiments have been accomplished with a 90-W solar panel under constant and changeable irradiations. Horizontally shaded area which changed from 0 to 80% has been applied to detect the impact of varying irradiation at appointed shading points. The results showed that for each 100W/m2 increase in radiation level leads to enhance the output power by 3.89 W, 3.37 W, 2.27 W, and 2.02W at 0 %, 25%, 50%, and 75% shaded area respectively. In addition, the efficiency has been raised by 0.29 %, 0.27%, 0.25%, and 0.22% at 0 %, 25%, 50%, and 75% shaded area respectively. The drop in output power and efficiency were 12.41W and 2.3% respectively when the shading area increased by 10%. However, this study considers the horizontal shading and ignored the other types of shading. F. Bayrak et al (2017) [23], analyzed thermodynamic and electrical performance under the shading shape and shading ratios on 75 W polycrystalline PV. Horizontal, vertical and single cell shading at different percentage were applied. The results showed that at 100% shading rate, the power losses were 99.98 %, 66.93% and 69.92% for horizontal, vertical and cellular shading respectively. The gap of this research is that the results are obtained from a practical study only without simulating study. Gutierrezet al [24] presented the effortless approach to model and analyze the performance of PV module under partial shading using shading ratio. The shadow opacity and characteristics of shaded

area integrated in this approach. J. C. Teo et al (2018) [25], investigated the partial shading effect and the critical point that reduced the sensitivity of shading heaviness. Under various numbers of shaded modules and shading heaviness, The P-V characteristics showed that the PV string became impervious to gravity shad when the irradiance of shaded panels arrived a critical point. The results showed that when irradiation on the shaded modules on the PV system was between 1000 and 700 W/m2, the power dropped by about 6.2% for each 100W/m2 drops in the irradiation. However, when irradiation was between 700 and 0 W/m2, each 100 W/m2 drops in the irradiation, leads to drop the power by 0.24%. In [21] and this research, the results obtained from MATLAB/SIMULINK did not validated experimentally. In the present paper, different cases of partial shading with different percentages are analyzed experimentally and theoretically to determine its impact on power and efficiency of mono crystalline PV panel with 36 series connected cells and three bypass diode. Insulated material is employed as shading element in different cases with different percentage of shaded area. The I-V recorded and P-V calculated before and after applying shadow is utilized to find the power loss corresponding to this shadow.

2.   MODELING OF PHOTOVOLTAIC MODULE

PV module is the basic unit of power PV generation system. PV module has non-linear characteristics which depend on solar radiation and cell temperature. In this paper, PV module with 36 series connected solar cell is chosen. Figure 1. Shows the PV module model that is employed in this study. Besides, the irradiance (G) and temperature (T) with the electrical characteristics parameter of PV module such as, open circuit voltage (Voc), short circuit current (Isc) are shown in the figure. It is having 23.42V, 5.192A and 1.5 as open circuit voltage (Voc), short circuit current and ideality factor respectively, while series resistance value (Rs) is 0 ohm. Different cases are carried out using Matlab/Simulink to determine I-V and P-V characteristics (Table 1). To develop the model of PV, the solar cell block is taken from Sim Electronics block set-Matlab. The parameters of solar cell are defined in equations (1) and (2) [25].

$$I = I_{ph} - I_{rs} \left[\exp\left(\frac{V + I\,R_S}{a V_T}\right) - 1\right] \tag{1}$$

Where:

$$V_T = \frac{N_S\,k\,T_c}{q} \tag{2}$$

The output powr is [26]

$$P_m = I_{max} V_{max} \tag{3}$$

Fill factor (FF) represents the ratio of maximum power divided by the open circuit voltage and short circuit current [26]

$$F.F = \frac{P_m}{P_{th}} = \frac{V_{max}\,I_{max}}{V_{oc}\,I_{sc}} \tag{4}$$

I, I_{Ph} and I_{rs} are the output, photo-generated and the diode saturation currents respectively, V is the output voltage, R_S is the series resistance, N_S is the number of cells, V_T is the junction thermal voltage, A is the ideality factor, k is the Boltzman constant (1.3806503×10-23 J/K), T is the cell temperature and q is the electron charge (1.6021765×10-19 C).

Different cases were conducted as illustrated in Table 2. The adopted PV module includes 36 solar cell which are divided into two group, each group consist of 18 cells. Different solar irradiations and constant temperature (25°C) were applied to find their effect on the I-V and P-V curve of the PV model. Shading factor (FS) represents the ratio of irradiance on the shaded Surface ($G_{T,S}$) to the irradiance on the unshaded surface (G_T) [27].

$$F_S = \frac{G_{T,S}}{G_T} \tag{5}$$

Table 1. Cases studies carried out

Case study	Solar Cell Irradiance (W/m^2)		Shading Factor
	Unshaded group (18 cells)	Shaded group (18 cells)	(FS)
Case 1	1000	1000	1
Case 2	1000	800	0.8
Case 3	1000	600	0.6
Case 4	1000	400	0.4
Case 5	1000	200	0.2
Case 6	1000	0	0
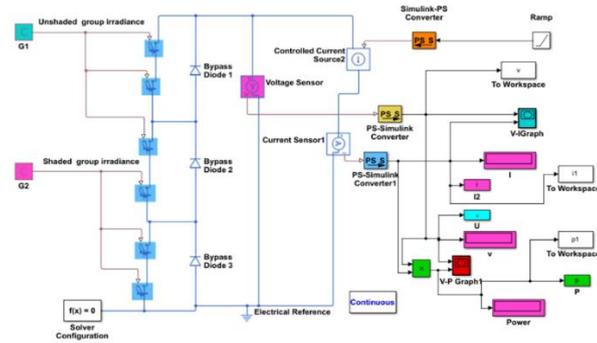
Figure 1. Photovoltaic module model with three bypass diodes

In addition, other cases were considered by applying different irradiation level on three groups of solar cells (each group 12 cells) as shown in Table 2 the model in Figure 1 used in these cases with simple changes.

Table 2. Illustration of random radiation levels for PV module.

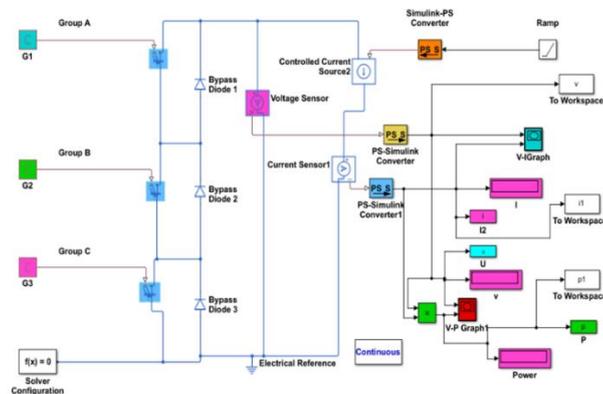| Case study	Solar Cell Irradiance (W/m^2)		
	Unshaded group A (12 cells)	Shaded group B (12 cells)	Shaded group C (12 cells)
Case1	1000	1000	1000
Case 2	1000	900	800
Case 3	1000	800	600
Case 4	700	600	200
Case 5	800	950	300
Case 6	300	500	700
Case 7	300	200	400
Case 8	200	200	200

Figure 2. Photovoltaic module model (three group with different irradiation levels)

Figure 3 shows the PV module, the vertical string shading with 100% shading area are applied to the model and the results are compared with the experiment results.
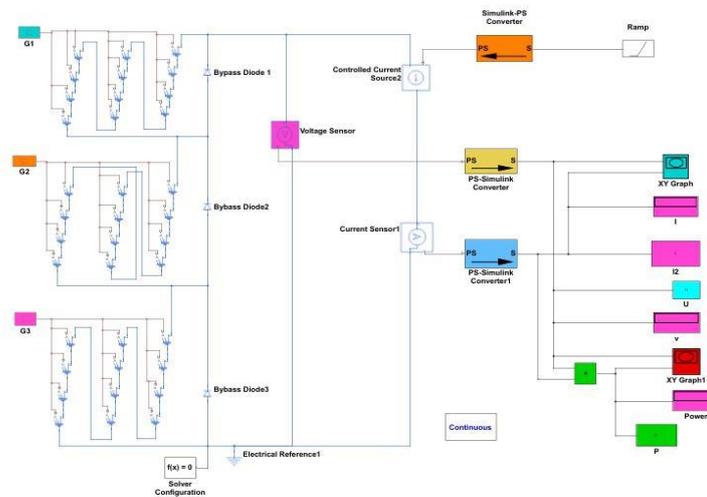
Figure 3. PV module and the experiment results

3.   EXPERIMENTAL SETUP

In order to obtain the I-V and P-V characteristics of the PV panel under partial shading, the current and voltage were measured. Solar radiation and ambient temperature affect these characteristics therefore; it is necessary to measure these parameters. At environmental conditions, the change in atmospheric condition may lead to rapid change in the solar radiation therefore; the data must be recorded quickly in short time as possible.

Figure 4 shows the experimental setup, where the experiment was set up in Baghdad (33.33° N latitude and 44.39° E longitude) for collecting the required data. The utilized PV pane is Monocrystalline PV panel with 36 cells connected in series, where each 12-cell connected to one bypass diode. The panel is placed on a mobile metallic holder and it is installed to face the south with an inclination of 31.2. Table 3 explains the electrical characteristics of the PV panel under standard test condition. The required data are radiation intensity, ambient and module temperatures, wind speed and relative humidity therefore; two digital multi- meters used to measure the current and voltage. Thermocouple type k was used for obtaining the panels temperature by using a digital data recorder. Relative humidity and ambient temperatures were measured by using UNI-T UT332 digital Thermo-hygrometer devise. The measurement of wind speed was obtained using wind gage type Kaindl Wind master 2.

Solar radiation was measured by solar meter pyrometer type TES 1333R and rheostat (100W, 10Ω) were used as load to measure the maximum current and maximum voltage. Many experiments were carried out in clear sky condition during September, 2018 to investigate partial shading on the panel. Different cases with different percentage of shading were applied on the panel by using non-transparent material as shading element to closing as 0, 25, 50, 75, 100% shaded area of horizontal string, vertical String and single cell as illustrated in Figure 5 and 6. Moreover, diagonal shading also investigated as shown in Figure 7.

Table3. Electrical characteristic of monocrystalline solar panel

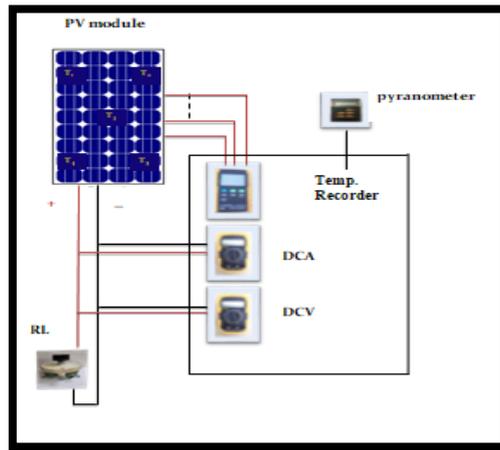| Designation	Abbreviation	Values
Maximum power	Pmp	88
Open circuit voltage	VOC	23.42 V
Short circuit current	ISC	5.192 A
Voltage at maximum power	Vmp	18. 33 V
Current at maximum power	Imp	4.801 A
Voltage temperature coefficient	Kv	-2.10 mV/cell/°C
Current temperature coefficient	Ki	15 micro A/cm2/°C
No. of cells connected in series	NS	36

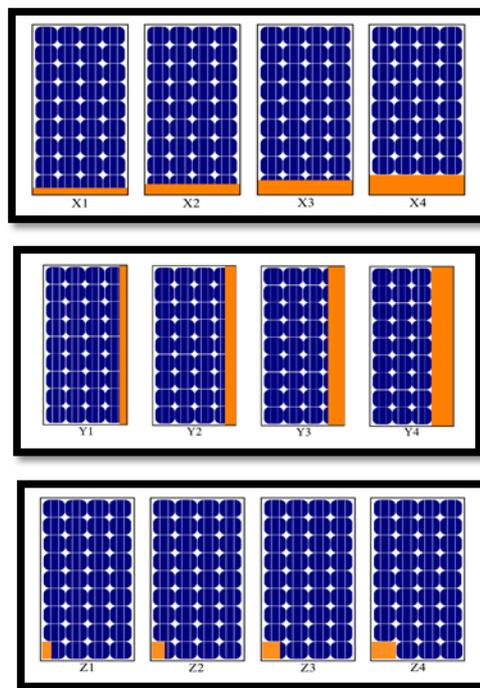Figure 4. The schematic view of the experimental setup

Figure 5. Different percentage of shading for horizontal string, vertical string and single cell by employed insulated materials; (X1) SA=25%, (X2) SA=50%, (X3) SA=75% and (X4) SA=100%, (Y) SA=25%, (Z1) SA=25%.
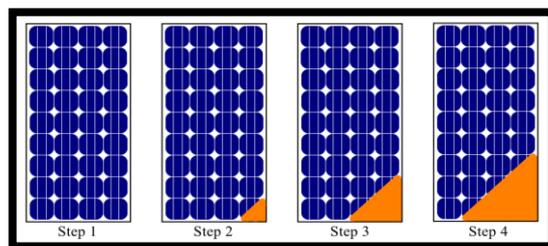

Figure 6. Diagonal shading profile of the photovoltaic panel with different steps

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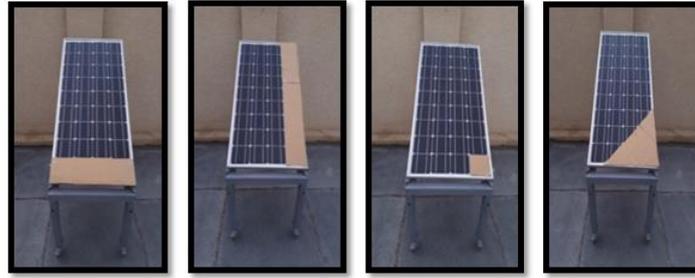
Figure 7. PV panel with different cases of shading (A) horizontal, (B) vertical, (C) single cell and (D) diagonal.

4.   RESULTS AND DISCUSSION

4.1. Simulation results

Figure 8 Shows the I-V and P-V characteristics of the photovoltaic module. This module consists of two groups, each group with 16 solar cells. The irradiance level on the first group (unshaded) is constant (1000W/m^2), while the irradiance level on the second group (shaded) between 1000 and 0W/m^2. Figure 8 (a) represents the I-V characteristics under the cases study in Table1. Figure 8 (b) illustrates the P-V characteristics of the same cases. From these results, it can be notice that the short circuit current decreases when the irradiance decreases, while the open circuit voltage is less affect by shading. The maximum power output decreases with decreasing in the shading factor. However, the output power is 88W at Fs=1 and then dropped to 72.52, 53.5, 36.7, 15.5 and 11.86 W for 0.8, 0.6, 0.4, 0,2 and 0 of Fs respectively.
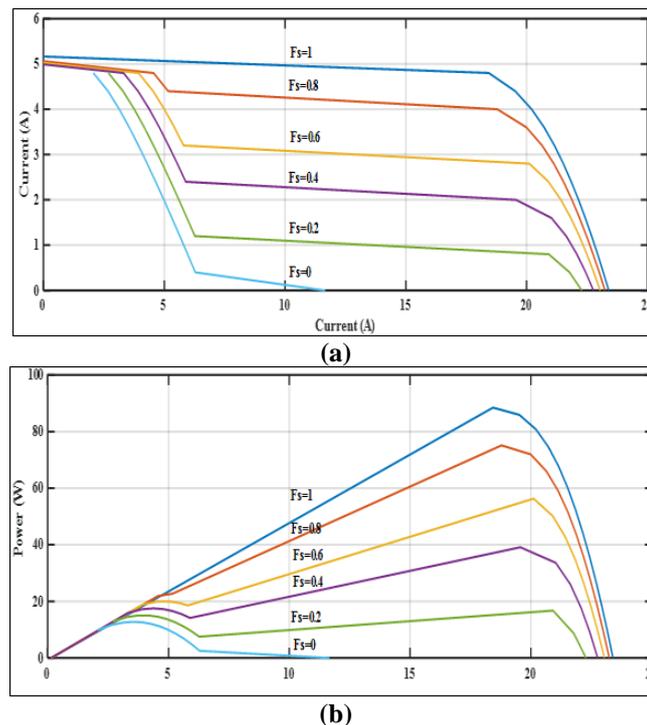

(a)

(b)

Figure 8. Photovoltaic module characteristics (a)I-V, (b)P-V.

When the irradiance on the module is non-uniform as illustrated in Table 2, multi steps in the I-V characteristics and multiple peaks in the P-V characteristics curves are observed. This is because the bypass diodes are activated, where this bypasses the shaded group cells and allow the unshaded group cells to have different P-V characteristics from the shaded group cells. Figure 9 (a) shows the simulation results of the cases study in Table 2. The same figure shows that the short circuit current is negatively affected by decreasing the irradiance levels. This leads to decrease the maximum current and consequently, the

maximum power as well, whereas the open circuit voltage is less affected by partial shading in comparing with short circuit current under these conditions. The maximum power values for these cases are 88, 76, 56.9, 33, 44.3, 29, 16.1 and 15W for first, second, third, fourth, fifth, sixth, seventh, eighth case respectively.
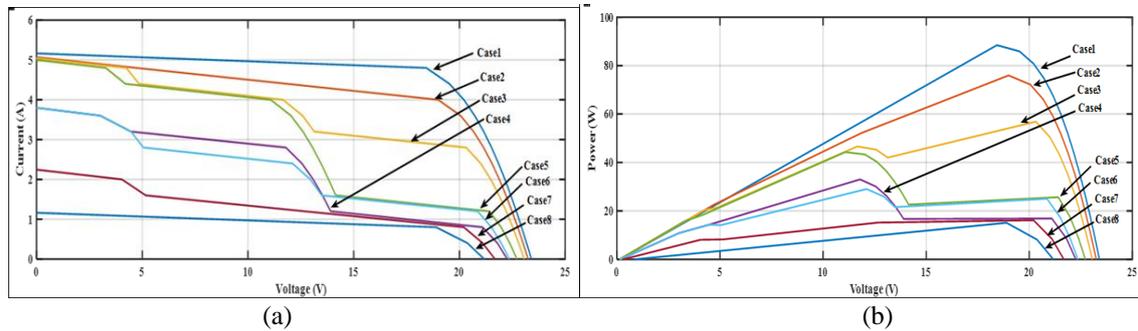

Figure 9. Photovoltaic module characteristics under nonuniform irradiation levels (a)I-V, (b)P-V.

4.2. Experimental results

An experiment was conducted to analyze the performance of PV panels under shading conditions. Figures 5, 6 and photo of Figure 7. Show the cases of shading with different shading area.
I.   Horizontal string with 0, 25, 50, 75, and 100% shaded area.
II.   Vertical String with 0, 25, 50, 75, and 100% shaded area.
III.   Single cell with 0, 25, 50, 75, and 100% shaded area.
IV.   Diagonal shading with multi step (one, two, three, and four steps).

Each case were applied on monocrystalline panel which shaded by 25, 50, 75, 100% respectively under radiation changes between (985±7 W/m2). In addition to that, the recorded environmental temperatures were close during measurement days. The outside temperature is 42±2°C while, the module temperature is approximately 66.2±2 °C. In general Isc, Im decreasing with increasing shaded area, consequently Pm decreasing with increasing shading area as showed in Figure 10, Figure 11 and Figure 12. Figure (5.10) a and b show I-V and P-V for different shading ratio of horizontal shading. Table 4 presents the Imax, Vmax, Pmax, ΔP, Plosses (ΔP/P (%)) and FF values which are calculated from Figure 10. Fill factor (FF) is decreased from 70.61% to 0.42%. It can. In comparison with current at no shading, the current is decreased by 98%. The maximum power at no shading 63.45W while, at 100% shading conditions, the power was drops to 0.504 W. In the other words, the power decreased by 99.36 % for 100% shading condition. In this case of shading, each string in the photovoltaic module affected by shading, therefore, the bypass diodes which connected between them completely disabled.

Case II: Vertical string shaded as previous case applied and the results explained in Figure 11. It can be noticed that the power output at 0% shading was 63.62W. While, at 100% shading condition, the power was decreased to 29.1W. In comparison with power at no shading, it mean that the power output dropped by 54.26% at 100% shading condition. At these condition, the F.F decreasing from 69.84% to 48.92%.

Case III: In this case single cell shaded by 25%, 50%, 75% and100%, the result clarified in Figure12. It can be noticed that at no shading (0% shading) the current is 4.7A, however, at 100% shading conditions, the current was 2.81A. The same figure showed that the power at no shading is 63.87W, and then dropped to 26.33 W. This means that power decreased by 68.71 % as the shading increased to100%, as compared With power at no shading condition.

Table 4. The shading results of three cases

Shading Area (SA)	Horizontal string Shading Case I			Vertical string Shading Case II			Single cell Shading Case III		
	ΔP (W)	P_{losses}(%)	F.F (%)	ΔP (W)	P_{losses}(%)	F.F (%)	ΔP (W)	P_{losses}(%)	F.F (%)
0%	0	0	70.61	0	0	69.17	0	0	70.5
25%	21.11	33.27	67.62	17.09	26.86	50.24	16.9	26.46	57.04
50%	36.78	57.96	63.43	20.15	31.67	50.07	21.69	33.96	50.04
75%	51.44	81.07	54.31	23.37	36.73	47.78	26.43	41.38	45.47
100%	62.95	99.21	0.4	34.52	54.26	48.92	37.5	58.71	49.3

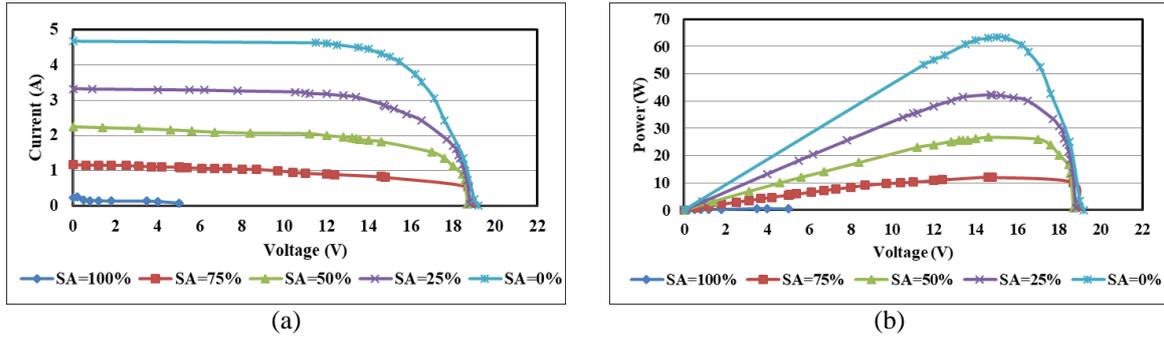(a)   (b)

Figure 10. Recorded characteristics of PV panel under horizontal string shading (a) I –V; (b) P-V.
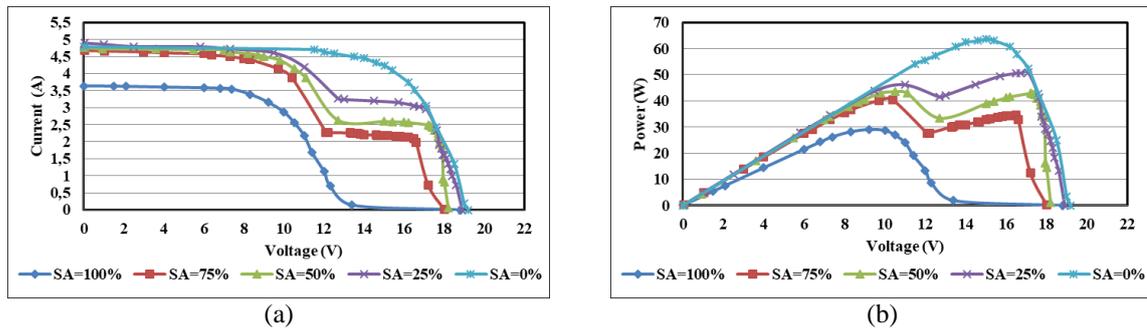

(a)   (b)

Figure 11. Recorded characteristics of PV panel under vertical string shading (a) I –V; (b) P-V.

(a)   (b)
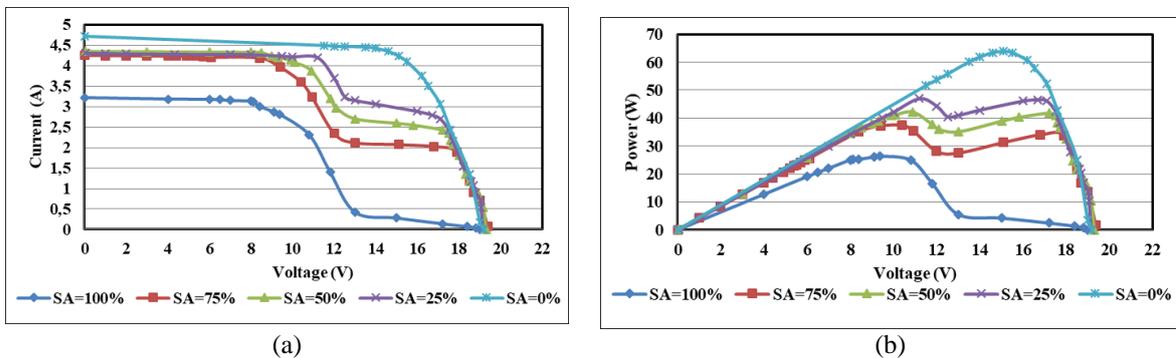
Figure 12. Recorded characteristics of PV panel under single cell shading(a) I –V; (b) P-V.

By comparing the results of the three cases, it can be concluded that the decreasing in maximum power output in the third case is less than the decreasing in the first cases (horizontal and vertical shading). Diagonally shading with multi step (one, two, three, and four steps) investigating at 860 W/m2 radiation level, as illustrated in Figure (5.19a & b). The results of this type of shading appeared that in the first step where no shading applied the Im was 4.38, then it decreased to1.9, 4.11, and 2.11A for second, third and fourth steps. On the other hand he power dropped from 61.32W at no shading to 2.43W for the fourth steps.

The comparison is done for two cases random reading for no shading condition and 100% of vertical string shading when solar radiation is 743 Wlm2 and module temperature is 57°C. The I-V and P-V curves of the collected data that were achieved experimentally and theoretically are explained in the Figures 14 a and b. The error between the experimental and theoretical results is about 3.3 and 6.28% for first and second cases respectively.

A comparison between present experimental results of power losses of PV module as a function of shading area with the experimental results of previous studies explained in Figure 15. This figure presented a

comparison of the present work with F. Bayrak et al [23]. It can be observed that the present experimental results have obvious agreement in the behavior as compared with the existing literature.
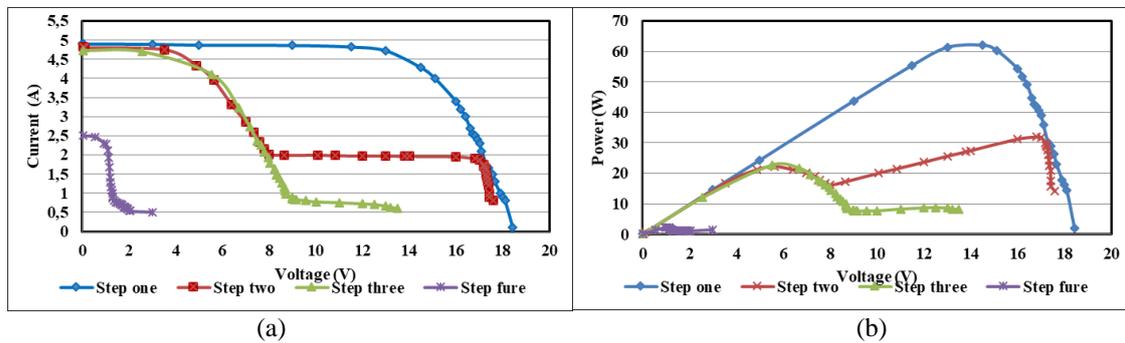

| (a) | (b) |

Figure 13. Recorded characteristics of PV panel under diagonally shading (a) I-V; (b) P-V.

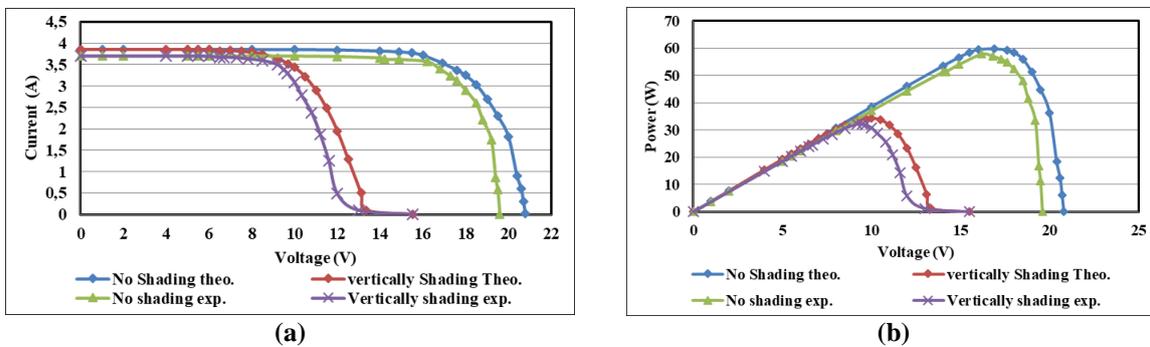| **(a)** | **(b)** |

Figure 14. Recorded characteristics of theoretical and experimental results for no shading and 100% vertical string shading. (a) I-V; (b) P-V.

5.   CONCLUSION

In this paper, non- transparent material with different shading position and different percentage of area are applied on monocrystalline solar panel. The importance of the presence of diodes in the PV panels is their ability to divide each panel into several sections. The results showed that the Photon current under partial shading decreases. This reduces Isc and Im, which leads to decrease the output power. Besides, the results reveals that when the radiation changes between 965 to 975 W/m2 and 100% shading condition is considered the power decreases by 99.36 %, 43.7 % and 41.15% for horizontal, single cell, and vertical respectively comparing with their initial value at no shading condition. Further, when considering the diagonal shading with no shading at first step the power is 62.06W. However, the power decreases by 48.56 %, 63.3% and 96.22% for second, third and fourth steps respectively. The parameters of PV panel are simulated by using MATLAB to investigate the partial shading effect at different irradiation levels. The results show noticeable agreement between the experimental and the theoretical results.

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