SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 21, No. 3, October 2024, 359-373

UDC: 621.383.51 **DOI: https://doi.org/10.2298/SJEE2403359B**

Experimental Study of the Shadow Effect on a Monocrystalline Silicon Photovoltaic Module

Hadjer Bounechba[1], Abdelfettah Boussaid[2], Mustapha Wassim Benlabed[3], Nidal Mouat[3]

Abstract: The ultimate component of photovoltaic energy conversion into electrical power is the solar cell. The best efficiency of this conversion is obtained for a group of few cells in parallel or in series, forming what is called “a solar module”. This grouping requires special precautions in order to avoid panel degradation, occurring when the amount of incident radiation received by a photovoltaic module is not the same (Shading Effect). This results in a dispersion of cell parameters, some cells become resistive and heat up (hot spots), thus producing significant power dissipation and reducing the characteristics of the PV module. In order to preserve the solar panel and lessen the shadow affect, bypass diodes are utilized. In the present research, a Matlab/Simscape model is used to plot I-V and P-V panel characteristics, under different numbers of shaded cells, with and without bypass diodes to illustrate the effects of partial, total and random shading on the PV module performance. Furthermore, our aim is to show how adding bypass diodes changes the performance of a partially shaded solar system. Experimental tests were carried out within the Frères Mentouri Constantine 1 University of Constantine / Electrical Engineering Laboratory (LEC) in order to study the effects of total, partial and non-uniform shading of mono crystalline silicon photovoltaic module (80W) with 36 cells connected in series (every 18 cells in the panel have one bypass diode). The obtained experimental data indicate that the PV module power decreases up to almost 50% in case of full shading, and up to 30% in case of application of partial shading.

Keywords: PV module, Shading Effect, Bypass diode, Incident radiation, Hot spots.

1 Introduction

In recent years, an increase in the global use of electricity is marked. This is due to the rise of industrial, transportation and communication resources [1]. However, most electrical energy is produced by the combustion of non-renewable

[1]Département d’électrotechnique, Université Constantine 1, Frères Mentouri, 25000 Constantine, Algeria; E-mails: Hadjer.BOUNECHBA@lec-umc.org
[2]Institut des Sciences et Techniques Appliquées, Université Constantine 1, Frères Mentouri, 25000 Constantine, Algeria; E-mail: Abdlfettah.BOUSSAID@lec-umc.org
[3]Université Constantine 1, Frères Mentouri, 25000 Constantine, Algeria; E-mails: wassimben9825@gmail.com, nidal.mouat@gmail.com

resources (coal, oil, gas, nuclear) whose exhaustion time is estimated at a few years [2]. In addition, this type of energy production is very polluting [3]. The development of non-polluting renewable energy sources is therefore topical [4].

The sun is the prime source for many renewable energy sources. Its radiation serves as an energy transport vector that can be utilized either directly or indirectly [5].

Photovoltaic energy is produced by directly converting solar radiation into electrical power that can be used immediately or stored for later use [6, 7]. This conversion is accomplished by a photovoltaic cell, its working principle is derived from the photovoltaic effect described as a physical process [8, 9].

A photovoltaic cell is characterized by a nonlinear current-voltage curve (I-V) representing all the electrical configurations that the cell can take [10]. The characteristic shape depends on many other factors such as the semiconductor type, the insolation and the cell temperature [11].

Under optimal sunshine conditions, the solar cell voltage V_{opt} will be between 0.5 V and 0.7 V [12]. Therefore, photovoltaic modules are usually composed of cells connected in series in order to boost the overall voltage of the modules and facilitate the electricity use [13, 14].

These types of associations can be made by grouping cells without any difficulty. However, it is recommended to use cells with very similar electrical characteristics to avoid any difference and loss of performance [15].

Cells' masking produces significant power losses [16] when the current difference between shaded and non-shaded cells is large, the voltage across the cell becomes negative and switches to receiver mode. A shaded cell can experience excessive reverse voltage or excessive current flow, resulting in enormous power dissipation in the form of heat. The accumulated heat may cause hot spots on the cells and damage the encapsulation materials of the photovoltaic modules [17].

Therefore, for a photovoltaic installation, it is essential to equip it with electrical protection (bypass diodes) to increase its lifespan and avoid destructive breakdowns related to the association of cells and their operation in the shade event [18, 19].

Theoretically, to ensure the best system efficiency, one diode should be used per cell. However, to simplify the production process and limit the modules' cost, manufacturing industries generally use one diode for 15 or 24 cells [20].

The conduction of these diodes impacts the output characteristic of the PV generator by the presence of multiple local maxima instead of a global maximum, thus making maximum power point tracking difficult [21 – 23].

The purpose of this research paper is to analyze the shading effect problem and determine its influence on the voltage, current, power and electrical efficiency of mono crystalline silicon PV module with two bypass diodes and 36 cells in series.

Using Simscape/Matlab, the model was simulated to get the I-V and P-V characteristic curves for the 80 W solar panel. Then, we validated the model with experimental results of STP080S-12/Bb PV module under total, partial and random shading effect. These tests were carried out at the Laboratory of Electrotechnics of Constantine (LEC)/Frère Mentouri University of Constantine 1.

In the remainder of this paper, we present the theoretical aspect related to this work before moving on to the technical details. Therefore, Section 2 provides the mathematical description of a PV module while Section 3 describes the shading effect. The hardware implementation as well as the validation of the proposed system are detailed in Section 4. Finally, Section 5 presents the conclusions drawn from this work.

2 Mathematical Modeling of PV Module

Fig. 1 presents the equivalent circuit diagram of a photovoltaic cell when exposed to illumination. This diagram depicts a current generator (I_{Ph}) coupled in parallel with a diode, with two parasitic resistances [24].

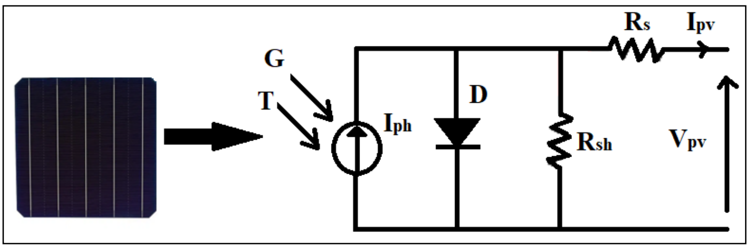


Fig. 1 – *Simplified equivalent circuit of PV module.*

To plot the nonlinear characteristics, *I-V* and *P-V* of PV module we assume that the shunt resistance R_{sh} is infinite, and we neglect it.

The equations describing the static behavior of a conventional diode's PN junction are as follows [25]:

$$I = I_{ph} - I_s\left(\exp\left(\frac{q(V+IR_s)}{AKT}\right)-1\right), \tag{1}$$

$$I_{ph} = I_{sc} + K_i\left(T-298\right)\frac{G}{1000}, \tag{2}$$

$$I_S = I_{S0}\left(\frac{T}{T_{ref}}\right)^3 \exp\left[-\frac{qE_g}{AK}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right], \tag{3}$$

where I_{ph} is the generated photocurrent (A), I_s is the reverse saturation current of diode (A), R_s is the series resistance of PV cell (Ω), V and I, refer to PV cell output voltage and current, T_{ref} and G are respectively the reference temperature and the solar irradiance (W/m^2), q is electron charge (C), K is Boltzmann constant, A is ideality factor, E_g is the energy bandgap and T is the cell temperature (K).

The fill factor, FF, is the ratio of the maximum power P_m to the product of open circuit voltage V_{oc} and short circuit current I_{sc} [26]. The maximum power point is associated with the maximum voltage V_m and current I_m.

$$FF = \frac{P_m}{V_{oc} I_{sc}} = \frac{V_m I_m}{V_{oc} I_{sc}} . \tag{4}$$

Solar cell efficiency, η, is defined as being he ratio of the cell's maximum power output, P_m and the incident illumination, P_{in}, on the surface of the cell [27].

$$\eta = \frac{P_m}{P_{in}} = \frac{V_m I_m}{E S_c} , \tag{5}$$

where S_c is the surface of the cell and E is the irradiance (W/m^2).

In this study, we chose the PV module to be simulated (36 cells in series), whose technical characteristics given by the manufacturer under standard conditions (G = 1000 W/m², T = 25°C, AM1.5) are mentioned in the **Table 1**.

Table1

Manufacturer's specifications for the PV module.

Parameters	Information
Brands and type	STP080S-12/Bb
Maximum power	80 W
Current at P_{max}	4.58A
Voltage at P_{max}	17.5V
Short-circuit current	4.95A
Open- circuit voltage	21.9V

3 Shading Effect

It is possible that obstacles of any kind (buildings, trees, etc.) may shade the solar panels. Shadows on photovoltaic collectors can lead to losses in energy production. Production loss depends on the size and density of the obstacles.

Shades can be full or partial. Full or complete shades cover the entire panels (covers, clips, dirt of all kinds, etc.) while partial shades allow some sunlight to pass through. PV cells are connected in series. Therefore, the weakest unit can impact the performance of the other units. Thus, complete shading of a row of cells can render the entire photovoltaic module useless.

The shading factor effect, F_s is characterized by the ratio between the irradiance on the shaded surface G_{ts} and the irradiance on the unshaded surface, G_t.

$$F_s = \frac{G_{ts}}{G_t} . \tag{6}$$

The **Table 2** presents the cases studied in this work, using standard test conditions; with 18 shaded and 18 unshaded cells.

Table 2

Cases studied for the shading factor effect.

	Solar cell illumination (W/m^2)		Shading factor %
	Unshaded group (G_t)	Shaded group (G_{ts})	
Case 1	1000	700	70
Case 2	1000	500	50
Case 3	1000	300	30
Case 4	1000	100	10

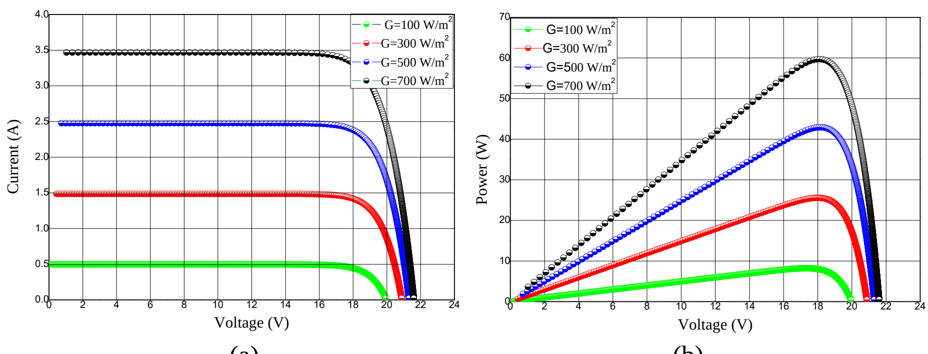


Fig. 2 – *Shading factor effect on PV module characteristics:* (a) *V-I and* (b) *V-P.*

From the characteristics V-I and V-P, it can be seen that each time the shading factor of the PV module is increased, the short-circuit current and the maximum power are reduced.

To solve these problems, PV modules are now equipped with bypass diodes (Fig. 3), which limit the shadow effect on certain panels [28].

To study the partial shading impact on monocrystalline PV module, various cases (in total four cases) are considered (Fig. 4):

– Case (a): 2.77% of the module is shaded (one cell).

– Case (b): 25% of the module is shaded (9 cells).

– Case (c): 33.33% of the module is shaded (12 cells).

– Case (d): 50% of the module is shaded (18 cells).

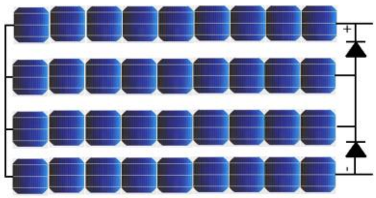


Fig. 3 – *PV module with two bypass diodes.*

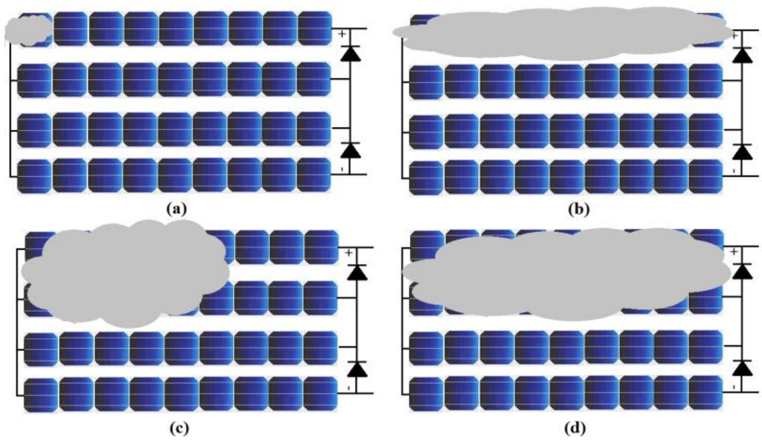


Fig. 4 – *PV module shading cases.*

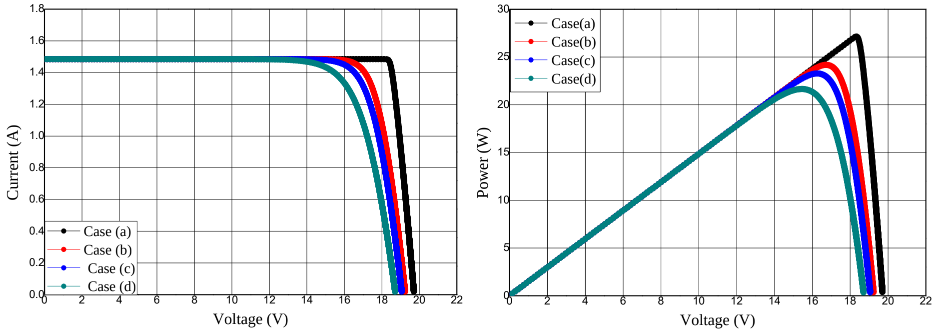
Fig. 5 shows the simulation results of the PV module under the four cases of shadow without bypass diodes. It should be noted that the illuminance of the shaded cells was reduced to G = 300 W/m^2 for all cases.

Table 3 gives the external photovoltaic parameters determined from the I-V and P-V characteristics of the solar panel for cases (a), (b), (c) and (d).

It is noted that the studied partial shading negatively affects the I-V and P-V characteristics of the solar panel because the cells are connected in series.

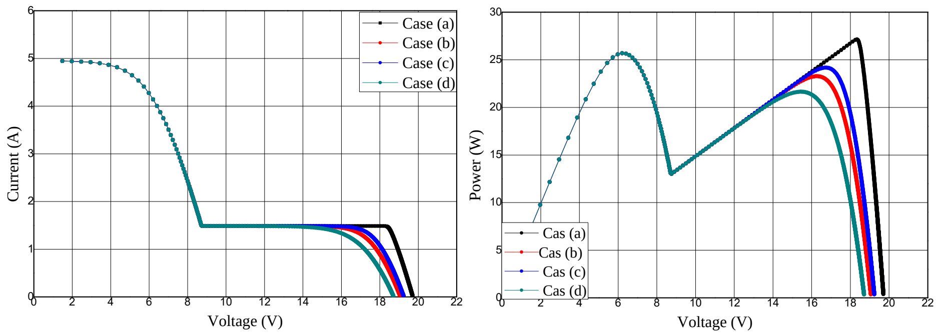
The current generated by 36 solar cells in series is the same throughout the photovoltaic panel and limited by the current of the weakest cell.

To solve these problems, we add a bypass diode into the simulation model for the four studied cases (Fig. 4).



(a) (b)

Fig. 5 – (a) *V-I and* (b) *V-P characteristics of the PV module under shading cases (a, b, c, d) without bypass diodes.*



(a) (b)

Fig. 6 – (a) *V-I and* (b) *V-P characteristics of PV module under shading cases (a, b, c, d) with two bypass diodes.*

Table 3

External photovoltaic parameters of the solar panel for cases (a), (b), (c) and (d).

	I_{sc} (A)	V_{oc} (V)	I_m (A)	V_m (V)	P_m (W)	P_{in} (W)	*FF*	η%
Case (a)	1.48	19.72	1.47	18.34	27.14	15.62	0.93	4.82
Case (b)	1.48	19.25	1.44	16.75	24.17	15.62	0.84	4.30
Case (c)	1.48	19.03	1.43	16.29	23.27	15.62	0.82	4.13
Case (d)	1.48	18.72	1.39	15.5	21.64	15.62	0.78	3.85

I-V and the P-V characteristics of the PV panel under shadowing effect with and without bypass diodes are evaluated. From Fig. 6 it can be observed that the occurrence of partial shading on a PV module with bypass diodes is accompanied by the generation of a power point above the maximum containing both local and global peaks.

Consequently, maximum power point tracking becomes problematic.

4 Experimental Section

This study is carried out in the Constantine Electrotechnical Laboratory (LEC), in the Constantine region whose geographical coordinates are 36.21° latitude and 6.38 longitude in the center of eastern Algeria [29].

The region is characterized by a continental climate that is hot in summer (25°C to 38°C with temperatures reaching 47°C) and cold in winter (–2°C to 12°C). Around 3216.25 hours of sunshine are counted in Constantine throughout the year. On average, there are 105.57 hours of sunshine per month [30].

Fig. 7 – *Geographical position of Constantine* [31].

For this experimentation, we used several pieces of equipment:

– 80 W monocrystalline PV module STP080S-12/Bb with a 30° angle and dimensions of 1195×541×30 mm, consisting of 36 identical silicon cells and two bypass diodes (Fig. 8).

– Two variable resistors of 33 Ω to receive the current supplied by the photovoltaic panel.

– Measuring instruments such as a voltmeter and an ammeter to measure the voltage and the global current.

– Pyranometer for the solar illumination.

– A dSPACE 1104 controller board was used as a platform to save current and voltage data; this is done using the input/output (I/O) of the dSPACE interface blocks.

– The voltage and current of the PV module are used as inputs to the dSPACE 1104 interface, while the LANGLOIS ISOL 720 and LEM (LA25-NP) sensors are used for data processing.

Fig. 8 – *PV module with two bypass diodes.*

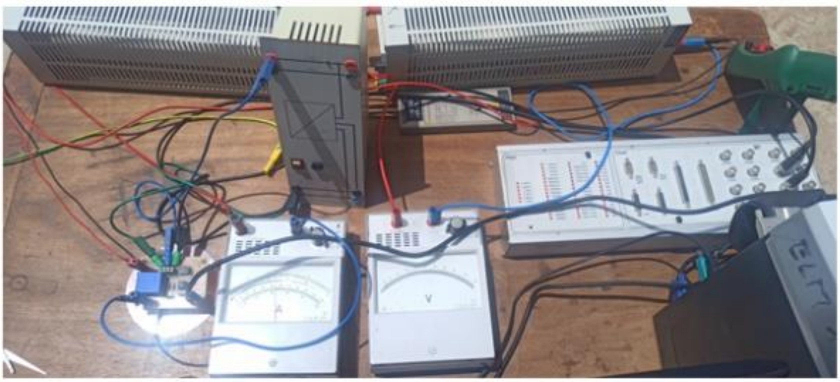


Fig. 9 – *Experimental setup.*

To determine the I-V and P-V characteristics of the PV panel under shadow effect, the current and the voltage at the terminals of PV panel must be measured and logged simultaneously.

Different types of shadows were applied on the test module to study the shadow effect on the panel energy production in different situations.

The shadow effect was artificially created by partially covering a part of the module with transparent yellow plastic cover. This cover reduces incident solar radiation by about 60%.

There are four tests of shading with different shaded area are studied to evaluate the performance of the PV module.

4.1 Test 1: No shading, partial shading, and total shading

Fig. 10 depicts the I-V and P-V characteristics of the PV module, which consists of 36 cells connected in series. The irradiance value for the first case is constant at 290 W/m^2 (unshaded). In the second case (partially shaded), it ranges between 290 and 250 W/m^2, while in the third case (fully shaded) it ranges between 290 and 0 W/m^2 at 23°C.

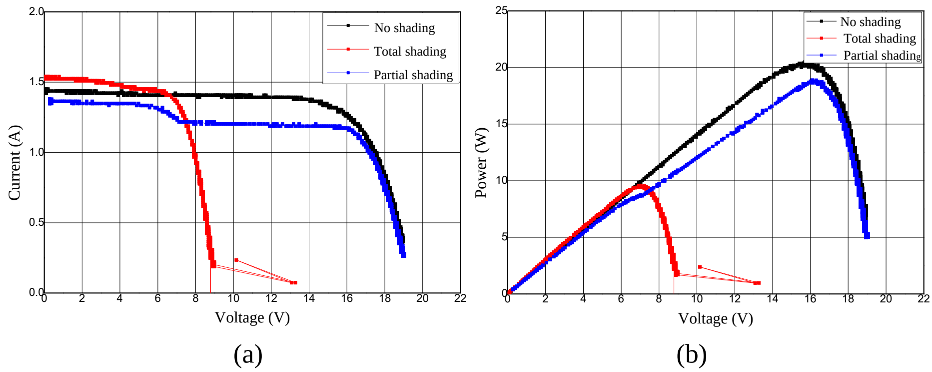


Fig. 10 – (a) *I-V and* (b) *P-V characteristics for monocrystalline Silicon PV module under; unshading, partial shading, and full shading effects.*

We can see from these results that when the irradiance decreases (partial shaded), the short circuit current and the maximum power output decreases, while the open circuit voltage is less affect by partial shading.

It is also observed that when total shaded is applied, the mono-Si module shows a significant decrease in open circuit voltage and in output power.

4.2 Test 2: No shading, 12 horizontal cells shaded, 12 vertical cells shaded

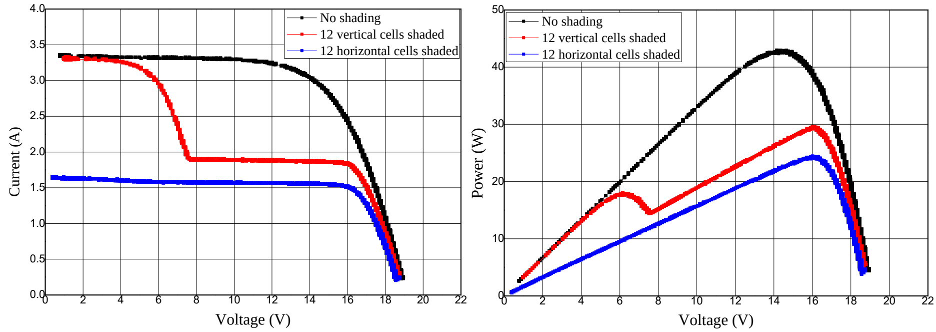
I-V and P-V characteristics of the PV module are presented in Fig. 11. This module consists of two bypass diodes and 36 cells connected in series and divided into two groups of 18 cells (1 bypass diode every 18 cells).

The shadowing effect was created on 12 cells; in the first case the 12 cells are in the same group of the first diode while in the second case, 6 cells are in the first group and 6 cells are in the second group.

The irradiance level is between 670 and 400 W/m^2 where the temperature is 40°C.

It is observed that the output power at no shading (0% shading) is 42.9W, while in the horizontal case the power decrease to 29.5 W.

In the vertical case the output power decreased from 42.9 W at no shaded area to 24.2 W at shaded area.



(a) (b)

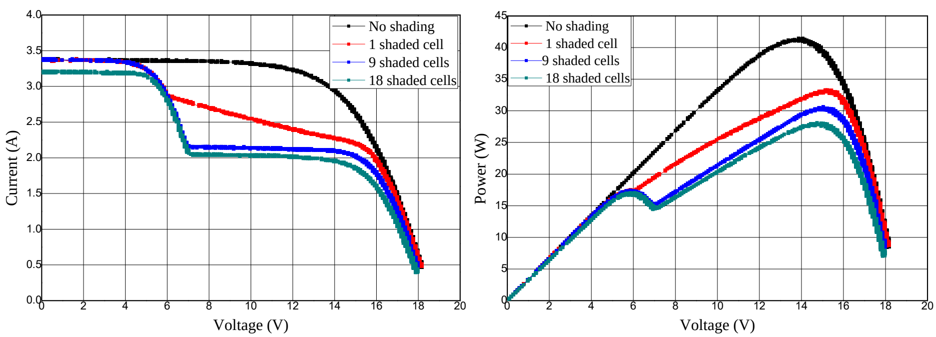
Fig. 11 – (a) *I-V and* (b) *P-V characteristics for monocrystalline Silicon PV module under; unshading, 12 horizontal cells shaded and 12 vertical cells shaded.*

4.3 Test 3: Unshading, 1 cell shaded, 9 cells shaded, 18 cells shaded

In this structure, we are interested in the effect of partial shading on the power produced by the photovoltaic panel. For this configuration, a device is placed above a PV panel to prevent direct sunlight from reaching the cell surface. We have used shading cover for different cells of the PV panel as 1 cell, 9 cells and 18 cells (Fig. 12).

(a) (b) (c)

Fig. 12 – *Different cases of PV panel shading* (a) *Single cell,* (b) *9 cells,* (c) *18 cells.*



(a) (b)

Fig. 13 – (a) *I-V and* (b) *P-V curves of the PV module when using bypass diodes under shading condition (1 cell, 9 cells and 18 cells).*

From Fig. 13, the output power of the PV module without shading is about 42.5 W. When 1 cell is covered, the power decreases and keeps decreasing with the increase in the number of shaded cells until it reaches 27.9 W when 18 cells are shading.

4.4 Test 4: Random shading

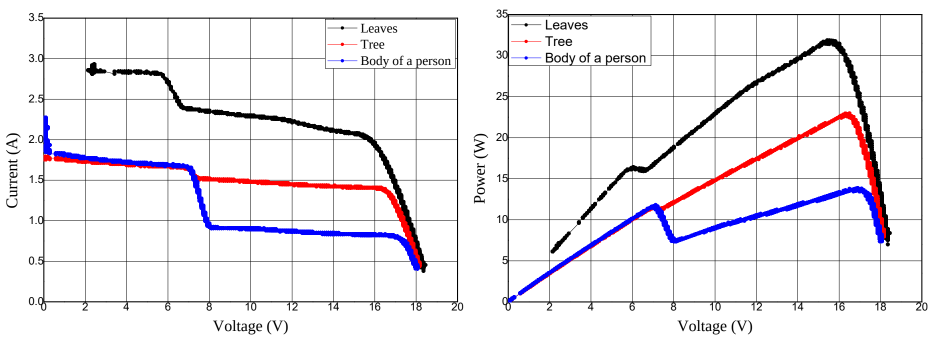
In this part of the experiment, for the same type of modules described above, we are interested in the random shading effect on PV modules. Indeed, three factors can cause this type of shading, they are trees, leaves or a person body (Figs. 14). This test was performed under the same lighting conditions to allow random shading to influence powering the photovoltaic panels.

(a) (b) (c)

Fig. 14 – *Different types of shading in a PV panel:*
(a) *leaves shading;* (b) *tree shading;* (c) *body shading.*

From Fig. 15, External factors can affect the performance of solar panels.

All elements that cause the deformation of the sun's radiation on the panel reduce their performance and must be taken into consideration.



(a) (b)

Fig. 15 – (a) *I-V and* (b) *P-V characteristics of the module under random shading.*

5 Conclusion

This research paper aims to study and analyze the performance of a monocrystalline silicon photovoltaic module, composed of 36 cells connected in series, under different shading effects. The impact of different shading configurations at different irradiation levels has been simulated using Matlab/Simscape software. According to the simulation results, the I-V and P-V characteristics of the PV panel are not only affected by the radiation amplitude, but also by the radiation distribution over the PV module.

To validate our results, an experimental study of four shading cases is carried out at the electrical engineering laboratory in Constantine (LEC), Algeria.

The study found that adding just two bypass diodes to the solar PV module increases the output power when the photovoltaic system is partially or randomly shaded.

More research is advised to examine and contrast the impacts of shade on PV characteristics while taking into account additional PV module types not included in this publication. This would give photovoltaic system users a more complete basis of choice. Matlab Simulink was used in this study and further research with another tool is recommended to examine the results in more depth and in other areas.

6 References

[1] A. Z. AL Shaqsi, K. Sopian, A. Al-Hinai: Review of Energy Storage Services, Applications, Limitations, and Benefits, Energy Reports, Vol. 6, December 2020, pp. 288 – 306.

[2] C. Zou, Q. Zhao, G. Zhang, B. Xiong: Energy Revolution: From a Fossil Energy Era to a New Energy Era, Natural Gas Industry B, Vol. 3, No. 1, January 2016, pp. 1 – 11.

[3] A. Grimaud, L. Rougé: Polluting Non-Renewable Resources, Innovation and Growth: Welfare and Environmental Policy, Resource and Energy Economics, Vol. 27, No. 2, June 2005, pp. 109 – 129.

[4] O. Ruhnau, P. Hennig, R. Madlener: Economic Implications of Forecasting Electricity Generation from Variable Renewable Energy Sources, Renewable Energy, Vol. 161, December 2020, pp. 1318 – 1327.

[5] A. M. Mitrašinovi: Photovoltaics Advancements for Transition from Renewable to Clean Energy, Energy, Vol. 237, December 2021, p. 121510.

[6] C.- H. Li, X.- J. Zhu, G.- Y. Cao, S. Sui, M.- R. Hu: Dynamic Modeling and Sizing Optimization of Stand-Alone Photovoltaic Power Systems Using Hybrid Energy Storage Technology, Renewable Energy, Vol. 34, No. 3, March 2009, pp. 815 – 826.

[7] K. Liu, D. Jia, Y. Sun, C. Wei, G. Geng: Optimal Allocation of Photovoltaic Energy Storage on User Side and Benefit Analysis of Multiple Entities, Energy Reports, Vol. 8, October 2022, pp. 1 – 13.

[8] A. M. Bagher, M. M. Abadi Vahid, M. Mohsen: Types of Solar Cells and Application, American Journal of Optics and Photonics, Vol. 3, No. 5, October 2015, pp. 94 – 113.

[9] T. Hariharasudhan, D. Prince Winston, M. Palpandian, M. Pravin: A Comparative Analysis of Polycrystalline and Bifacial Photovoltaic Module Under Various Partial Shading Condition, Energy Conversion and Management, Vol. 270, October 2022, p. 116223.

[10] F. B. Pelap, P. D. Dongo, A. D. Kapim: Optimization of the Characteristics of the PV Cells Using Nonlinear Electronic Components, Sustainable Energy Technologies and Assessments, Vol. 16, August 2016, pp. 84 – 92.

[11] I. H. Rusiana, Y. B. Zainal, S. Sambasri: Study and Analysis of Shading Effects on Photovoltaic Application System, Proceedings of the 1st International Conference on Industrial, Electrical and Electronics (ICIEE), Anyer, Indonesia, September 2018, p. 02004.

[12] A. Manor, E. A. Katz, T. Tromholt, F. C. Krebs: Electrical and Photo-Induced Degradation of ZnO Layers in Organic Photovoltaics, Advanced Energy Materials, Vol. 1, No. 5, October 2011, pp. 836 – 843.

[13] Y.- J. Wang P.- C. Hsu: Analytical Modelling of Partial Shading and Different Orientation of Photovoltaic Modules, IET Renewable Power Generation, Vol. 4, No. 3, May 2010, pp. 272 – 282.

[14] D. Prince Winston, S. Kumaravel, B. Praveen Kumar, S. Devakirubakaran: Performance Improvement of Solar PV Array Topologies During Various Partial Shading Conditions, Solar Energy, Vol. 196, January 2020, pp. 228 – 242.

[15] A. H. Numan, Z. S. Dawood, H. A. Hussein: Experimental Investigation of Photovoltaic Partial Shading Losses under Different Operation Conditions, Al-Nahrain Journal for Engineering Sciences, Vol. 23, No. 1, March 2020, pp. 35 – 44.

[16] A. H. Numan, Z. Salman Dawood, H. A. Hussein: Theoretical and Experimental Analysis of Photovoltaic Module Characteristics Under Different Partial Shading Conditions, International Journal of Power Electronics and Drive Systems, Vol. 11, No. 3, September 2020, pp. 1508 – 1518.

[17] M. Dhimish, V. Holmes, P. Mather, M. Sibley: Novel Hot Spot Mitigation Technique to Enhance Photovoltaic Solar Panels Output Power Performance, Solar Energy Materials and Solar Cells, Vol. 179, June 2018, pp. 72 – 79.

[18] S. Gallardo-Saavedra, B. Karlsson: Simulation, Validation and Analysis of Shading Effects on a PV System, Solar Energy, Vol. 170, August 2018, pp. 828 – 839.

[19] M. Palpandian, D. Prince Winston, B. P. Kumar, C. S. Kumar, T. S. Babu, H. H. Alhelou: A New Ken-Ken Puzzle Pattern Based Reconfiguration Technique for Maximum Power Extraction in Partial Shaded Solar PV Array, IEEE Access, Vol. 9, April 2021, pp. 65824 – 65837.

[20] B. B. Pannebakker, A. C. de Waal, W. G. J. H. M. van Sark: Photovoltaics in the Shade: One Bypass Diode Per Solar Cell Revisited, Progress in Photovoltaics: Research and Applications, Vol. 25, No. 10, October 2017, pp. 836 – 349.

[21] S. Li, H. Zheng: Energy Extraction Characteristic Study of Solar Photovoltaic Cells and Modules, Proceedings of the IEEE Power and Energy Society General Meeting, Detroit, USA, July 2011, pp. 1 – 7.

[22] A. Srinivasan, S. Devakirubakaran, B. Meenakshi Sundaram, P. K. Balachandran, S. K. Cherukuri, D. Prince Winston: L-Shape Propagated Array Configuration with Dynamic Reconfiguration Algorithm for Enhancing Energy Conversion Rate of Partial Shaded Photovoltaic Systems, IEEE Access, Vol. 9, July 2021, pp. 97661 – 97674.

[23] D. Prince Winstonet, K. Ganesan, P. Kumar Balachandran, D. Samithas, C. B. Baladhanautham: Experimental Investigation on Output Power Enhancement of Partial

Shaded Solar Photovoltaic System, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, Vol. 46, No. 1, June 2020, pp. 9793 – 9809.

[24] Vinod, R. Kumar, S. K. Singh: Solar Photovoltaic Modeling and Simulation: As a Renewable Energy Solution, Energy Reports, Vol. 4, November 2018, pp. 701 – 712.

[25] M. Karamirad, M. Omid, R. Alimardani, H. Mousazadeh, S. N. Heidari: ANN Based Simulation and Experimental Verification of Analytical Four- and Five-Parameters Models of PV Modules, Simulation Modelling Practice and Theory, Vol. 34, May 2013, pp. 86 – 98.

[26] D. Bernadette, M. Twizerimana, A. Bakundukize, B. Jean Pierre, N. Theoneste: Analysis of Shading Effects in Solar PV System, International Journal of Sustainable and Green Energy, Vol. 10, No. 2, June 2021, pp. 47 – 62.

[27] P. Singh, N. M. Ravindra: Temperature Dependence of Solar Cell Performance – An Analysis, Solar Energy Materials and Solar Cells, Vol. 101, June 2012, pp. 36 – 45.

[28] P. Guerriero, P. Tricoli, S. Daliento: A Bypass Circuit for Avoiding the Hot Spot in PV Modules, Solar Energy, Vol. 181, March 2019, pp. 430 – 438.

[29] Country Coordinate, GPS coordinate of Constantine, Algeria, Available at: https://www.countrycoordinate.com/city-constantine-algeria/

[30] Climate Data, Available at: https://en.climate-data.org/africa/algeria/constantine/constantine-499/ (https://www.mapz.com/export/checkout/preview/822867)