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COMPUTATIONAL ANALYSIS OF THE PERFORMANCE OF A PV MODULE UNDER THE EFFECT OF SHADING AND TILTING ANGLE

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Abstract. *Photovoltaic energy has many advantages, for instance, it does not pollute the environment, it has a large availability around the world, and in general, it is reachable by all the countries. However, this energy source has its performance affected by external and/or intrinsic parameters. Therefore, this study intends to analyze, via computer simulation, the shading and inclination angle influences on the photovoltaic module performance, acquiring the characteristics curves I-V and P-V using the software PV*SOL. Besides, the electrical efficiency in different configurations of shading and angles were studied. Analyzing the simulations, it is observed that the PV module tilted at 15° exhibited superior overall performance during the day, presenting the best results of dissipated power in a resistive load of 150 Ω. When there was shading on the PV module surface, it is verified a significant and proportional reduction of electrical power and maximum current, resulting in 1/3 maximum power reduction when 1/3 of the surface is shaded.*

Keywords: *Electrical efficiency, photovoltaic energy, PV*SOL, shading, tilt angle*

1. INTRODUCTION

The sun energy is necessary to life. Its uses to generate electrical energy via photovoltaic systems presented an increase in the last years around the world, due to a socio-environmental awareness and the cost reduction of photovoltaic technology. In Brazil, the increasing of this technology is the result of ANEEL (National Agency of Electrical Energy) regulation of distributed generation given by Normative Resolution nº 482/2012, which encouraged systems of microgeneration installed in houses and urban centers (Araújo, Rank, & Bueno, 2016; Dieter, 2018).

Besides the high reliability of the photovoltaic system, there are losses which impact on system efficiency. These losses can be from environmental conditions, such as shading and dirtiness, installation losses, such as modulo tilt angle, electrical losses because of wiring, etc. Therefore, these losses must be taken into account since the first step of the development of the photovoltaic project (Barbosa, 2010; Dieter, 2018).

When a photovoltaic module is exposed to an obstacle that causes shading on its surface inhibits producing energy, even when only one of the solar cell is receiving low light (Hickel, 2017). The solar cells are connected in series in polycrystalline silicon modules, thus, the cells rely on each other to generate electrical current, i.e., when a solar cell is affected by shading, the total electrical current generated by the module is decreased, and, consequently, the system generates less energy. The total current depends on the cell with lower yield (lower current), i.e., when completed shaded, the current trend to zero.

In addition to electrical damage, the shading impacts directly on the module efficiency, leading to a drop in energy generation of the affected module. To avoid such problems the photovoltaic modules are equipped with one or more bypass diode. They are installed in parallel to the rows of solar cells, becoming a better path to the electrical current when any panel cell is shaded (Rauschmayer, 2020).

The inclination angle consists of an important parameter that affects the direct irradiation absorption, and also in incident irradiation reflected by the module surface, i.e. directly impact the generation of electrical energy, consequently in the system performance. Accordingly, with Pinho and Galdino (2014), they asserted the best inclination angle for a PV module is directly related to the local latitude where the system is installed. However, angles close to 0° negatively affect the self-cleaning of the module surface, whereas such angles contribute to the accumulation of dirt and water on the absorption surface.

The presented research aims to analyze via computer simulation the influence of shading and tilt angles on the energy performance of a photovoltaic module, acquiring the characteristic curves I-V and P-V, and also the electrical efficiency using different configurations of shading and installation.

2. METHODOLOGY

In order to evaluate the effects of shading and the tilt angle on the performance of photovoltaic modules, this study utilized the simulation *software* PV*SOL programmed by the German company Valentin Software GmbH. The module used was the CS6P-265P-SD with maximum power of 265 W from Canadian Solar, whose electrical and mechanical characteristics can be verified in Table 1.

The module is installed over an elevated structure, composing an off-grid hybrid system photovoltaic-diesel developed by (Costa Júnior, et al., 2017), at Federal Institute of Maranhão / Campus Monte Castelo in the city of São Luís, Maranhão, geographically located at: latitude 2.5368297 S and longitude 44.2804442 W. This last information is very important due the results vary significantly in accordance with the system location.

Table 1. Photovoltaic module characteristics.
Adapted from (Canadian Solar Inc, 2016)

Photovoltaic Module: CS6P-265P-SD	
Manufacturer	Canadian Solar Inc.
Electrical data	
Cell type	Policrystaline silicon
Number of cells	60
Number of by-pass diode	3
Mechanical data	
Width	982 mm
Height	1638 mm
Depth	40 mm
Frame width	30 mm
Characteristics V-I at STC	
Voltage MPP	30,6 V
Current MPP	8,66 A
Nominal power	265 W
Efficiency	16,47%
Open circuit voltage	37,7 V
Short-circuit current	9,23 A

Information about the geographic location of the study and the technical characteristics of the photovoltaic module are entered as input data in the software. Other important parameters to be configured before the simulations are the mathematical models used to estimate the irradiance components from the global irradiance. In the context of diffuse irradiation in the horizontal plane, the Hofmann model was selected, in which the irradiance values for each minute are calculated with the aid of the clear sky model ($E_{\text{clear sky},i}$), given by Eq. (1) (Hofmann & et al., 2014).

$$E_{generated,i} = k_{t,i} \times E_{\text{clear sky},i} \tag{1}$$

where $k_{t,i}$ refers to the clear sky index defined as the ratio between the global irradiance measured at the Earth's surface ($E_{measured,i}$) and the global irradiance under clear sky conditions ($E_{\text{clear sky},i}$) in the same place. For the clear sky model, there is the angle of elevation of the sun (γ_S) and the extraterrestrial irradiance (E_{ext}), according to Eq. (2).

$$E_{\text{clear sky}} = 0{,}78 E_{ext} sen(\gamma_S)^{1{,}15} \tag{2}$$

Considering an inclined surface in β, the total irradiance incident on the inclined plane (E_{GT}) is composed of three main components and can be expressed through Equation (3) where E_b represents the direct irradiance on the inclined plane, E_g the irradiance reflected in the soil and E_d the diffuse irradiance in the sky (Padovan & Del Col, 2010).

$$E_{GT} = E_b + E_g + E_d \quad (3)$$

To obtain the diffuse irradiance on the inclined surface of the photovoltaic modules, the Hay and Davies model was selected, in which only the isotropic and circumsolar components of the diffuse irradiance are considered (da Silva, 2019). In this way, diffuse irradiance is obtained through Eq. (4):

$$E_d = DHI\left[\frac{DNI}{E_{ext}}\frac{\cos(\theta_s)}{\cos(\theta_Z)} + (1 - A_i)\frac{1+\cos(\beta)}{2}\right] \quad (4)$$

where *DHI* consists of diffuse irradiance in the horizontal plane, *DNI* is direct irradiance in the horizontal plane, θ_s is the angle of incidence, θ_Z the angle of zenith, and β the angle of inclination of the modules, as shown in Fig. 1.

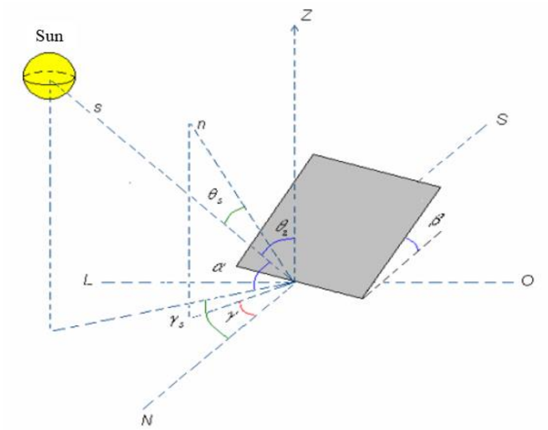

Figure 1. Direct incidence, panel inclination, and terrestrial azimuth angles.
(Oliveira, 2008)

Based on this model, Equation (3) can be rewritten and presented in its complete version according to Equation (5), in which we need the soil incident irradiance indexes (GHI) and the soil reflectance index (solar albedo).

$$E_{GT} = DNIcos(\theta_s) + GHIalbedo\frac{1-\cos(\beta)}{2} + DHI\left[\frac{DNI}{E_{ext}}\frac{\cos(\theta_s)}{\cos(\theta_Z)} + (1 - A_i)\frac{1+\cos(\beta)}{2}\right] \quad (5)$$

2.1 Analysis of the influence of the PV module tilt angle on the system performance

Seven photovoltaic modules were implemented in the software to investigate the tilt angle influence on the electrical power dissipated on a resistive load. The seven modules were configured with all the characteristics from the CS6P-265P-SD module from Canadian Solar, they were installed with their absorption surface facing North, each module is placed with different angles, varying between 0° and 30° with increment of 5°, as Fig. 2 shows. In this simulation, the presence of shading was not taken into account.

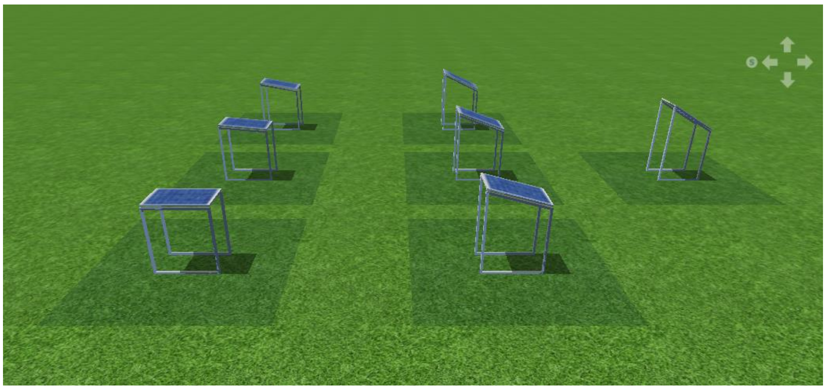

Figure 2. Layout of the modules to investigate the tilt angles influence on power.
Author (2020)

The voltage resulted from the simulation for the day 09 of January allowed to calculated the dissipated power in the load using the Ohm's Law equation, given by Eq. (6). For this, it was selected a resistive load of 150 Ω (Alencar and Martins, 2019).

$$P_d = V \times I \quad (6)$$

Where, P_d is the power dissipated, in W, V is the maximum peak voltage for each angle, in V, and I is the electrical current using the resistive load of 150 Ω, in A.

For the analysis of the influence of the tilt angles on the performance of the photovoltaic modules, the curves of the dissipated powers were plotted based on the calculated results indicating the behavior of the systems throughout the simulated day.

2.2 Analysis of the shading influence on the system performance

In this stage of the study, we sought to identify the influence of shading on the electrical efficiency of photovoltaic modules. For this, the computer simulation was carried out using June 21 at noon as a reference, making it possible to configure the affected area and the shape of the shadow from an obstacle inserted in PV * SOL, as shown in Figure 3. Hence, it was implemented in software seven photovoltaic modules configured with the technical characteristics of the Canadian Solar CS6P-265P-SD module and with different shading conditions for each module, as shown in Table 2.

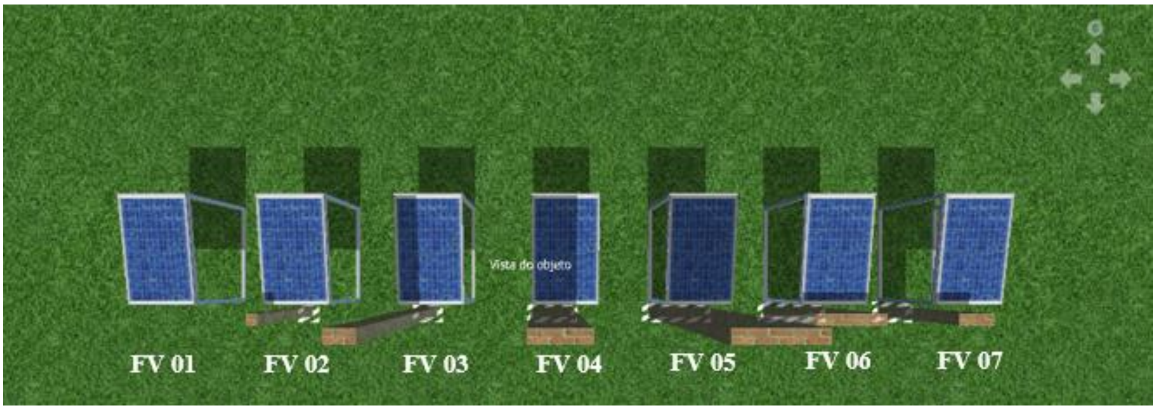

Figure 3. Layout of photovoltaic modules with different shading configurations.
Author (2020)

Table 2. Shading configuration simulated for each PV module.
Author (2020)

Module identification	Shading configuration
FV 01	Without shading
FV 02	1 cell shaded
FV 03	33% of surface area shaded (two rows of cells)
FV 04	66% of surface area shaded (4 rows of cells)
FV 05	Totally shaded
FV 06	10% of surface area shaded (horizontal shading)
FV 07	5% of surface area shaded (horizontal shading)

The simulation was realized three times, changing the tilt angles between 0°, 15° and 30°, to investigate and analysis of angle and shading influence on the system performance.

The electrical efficiency can be calculated using the ratio between the maximum electrical power produced and the radiation incident on the absorption area of the module. The produced power values are obtained through the P-V characteristic curves resulting from the simulation, and the irradiation values are shown in the database table exported from the PV * SOL *software*. Thus, it is possible to calculate the electrical efficiency of photovoltaic modules using Eq. (7) (Dieter, 2018; Pinho & Galdino, 2014).

$$\eta = \frac{Power\ [W]}{Irradiation\ [W/m^2] \times Module\ area\ [m^2]} \quad (7)$$

The characteristic curves I-V and P-V are obtained at the end of the simulations and the calculated electrical efficiency values were converted into graphs to analyze the influence of shading on the performance of the photovoltaic module.

3. RESULTS AND DISCUSSION

Figure 4 shows the results obtained from the powers dissipated for each angle of inclination of the photovoltaic module arranged per hour during the collection, and it was observed that all curves decline from 9 am to 12:30 pm. Simioni (2017) states that this effect of the power drop occurs due to the temperature increase in this period of the day, i.e., even if there is an increase in irradiation on the modules, its power decreases due to the temperature influence on the voltage generated on the module and, consequently, on the power dissipated. In the period from 12h30 to approximately 15h30, it is observed the increase in power and the reach of its maximum points, this is due to the reduction of temperature over time, and the level of irradiation that affects each module becomes the main parameter of influence on power, which also explains the sudden fall in power from 16 h. Analyzing the angles influences, it is noticed that the angle of 15° shows better average performance during the day, since smaller angles than 15°, despite reaching major power peaks around 15h30, they have the smallest performance practically all experimental day (from 9 am to 3 pm). Besides, the angles of 0° to 10° are inefficient in self-cleaning.

When analyzing the influence of the inclination angles, we notice that the 15° angle shows better average performance throughout the day, since the angles smaller than 15°, despite having a higher peak power at 15h30, have a less average performance during all the experiment (from 9 am to 3 pm). In addition, angles from 0 ° to 10 ° are inefficient in terms of self-cleaning the system.

The angles above 15° presented higher values of power during 9 h to 15 h, however, their peaks are small and after 15 h the power output dropped significantly, i.e. they had a lower performance in general.

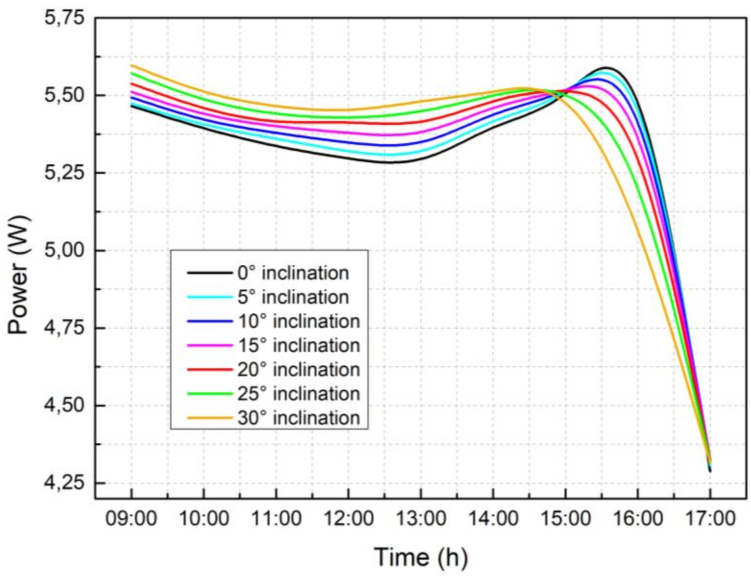

Figure 4. Dissipated power for each module on a resistive load for each tilt angle.
Author (2020)

In the simulations to study the influence of the shading parameter on the system performance, we obtained the characteristic curves I-V and P-V of all the photovoltaic modules analyzed. It can be seen through Figure 5 that there is a significant and proportional reduction in the maximum electrical power and electrical current due to the presence of shading on the surface of the photovoltaic module.

Note that the I-V and P-V curves of the PV 01 module are the only ones that do not present deformities as they depict a module without the presence of shading. However, the curves of the FV 02 and FV 03 modules are superimposed showing a loss of 1/3 of its performance, when compared with the performance of the FV 01 module. Thus, the performance of the FV 02 module with 1.65% of its shaded surface area, equivalent to a photovoltaic cell, is similar to the performance of the module with two entirely shaded rows (FV 03). This is due to the series arrangement of photovoltaic cells inside the module under study and the presence of three bypass diodes that allow the division of the PV module into three submodules, in order to reduce the impact of partial shading in power generation. In PV modules with cells in series and without bypass diodes, when a cell is shaded the performance of the system is reduced sharply, becoming similar to the performance of a fully shaded module (Faria, 2014; Pinho and Galdino, 2014; Zilles, Macêdo, et al., 2012).

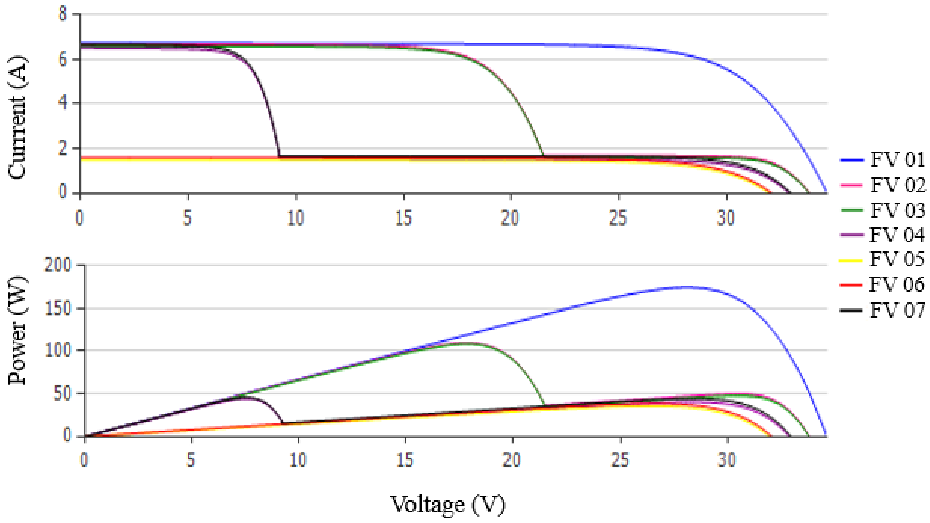

Figure 5. Characteristics I-V and P-V curves for PV module with 0º inclination
Author (2020)

The same behavior was observed in the curves of modules FV 04 and FV 07, where they are overlapping and with a loss of 2/3 of their performance. In the case of the FV 06 module with only 10% of its surface shaded, the same behavior of the module that is fully shaded (FV 05) is observed. In this case, when a PV cell in each row is shaded, it causes interference in the passage of electrical current between all cells that are connected in series of the module, resulting in a reduction in system performance and making it similar to a module with shading throughout its absorption surface, according to Zilles, Macêdo et al. (2012).

When comparing the electrical efficiency results obtained for the different inclination angles of the photovoltaic modules, it is observed that the influence of the inclination is minimal, in comparison with the influence of the shading parameter, as shown in Figure 6. It was noted that the larger the area shaded the lower the efficiency of the system because the generation of energy will be reduced. However, it appears that the module FV 03, which has vertical shading in 33% of its surface area, has higher efficiency than the modules FV 06 and FV 07, which have horizontal shading in only 10% and 5% of its area superficial, respectively. Therefore, we can see that the direction of shading, horizontal or vertical, is also a parameter that directly affects the performance of the system.

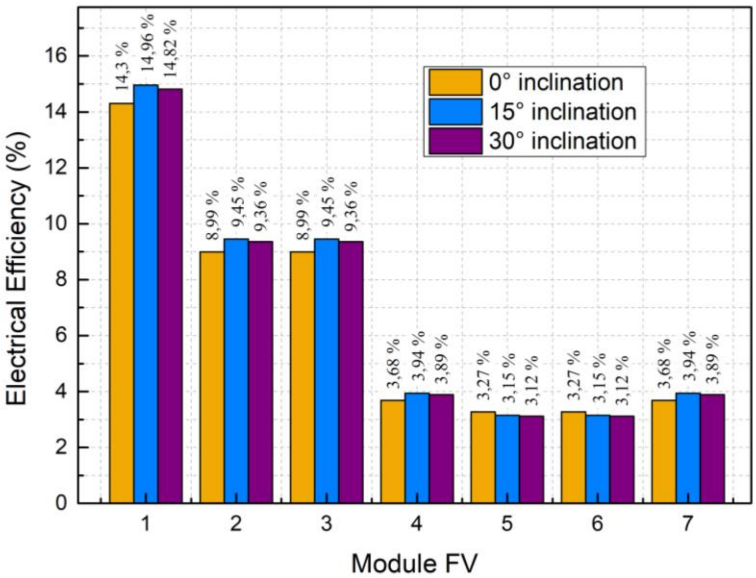

Figure 5. Shading and tilt angle influences on electrical efficiency of photovoltaic modules.
Author (2020)

The shading position influence can also be observed when comparing the efficiencies of modules FV 04 and FV 07. These modules present similar performance, even when module FV 04 has a larger surface area shaded than module FV

07. This is due to the module FV 07 shading is a horizontal type, affecting more cells rows than the vertical shading of module FV 04.

4. CONCLUSIONS

Some loss parameters directly affect the efficiency of photovoltaic systems and in this sense the present work sought to verify the effects of the shading and the inclination angles of the modules using simulations using the software PV*SOL.

In the study of the influence of the inclination parameter of the photovoltaic module, it was found that the angle of 15 ° has the best average performance of power dissipated between the angles of 0 ° to 30 °. However, when studied together with the shading parameter, the angle influence becomes secondary, the shadow configuration on the module has more interference than the angle with which it is inclined.

Regarding the shading parameter, its direct influence on the performance of the photovoltaic system was observed, standing out as the most relevant among all the parameters studied in this work so far. Even affecting small areas of the absorption surface of the module, depending on its direction, the shading can result in significant power losses, as it was found in a shading along the short edge of the photovoltaic module, horizontal direction for the configuration used, which affects only 10% of the absorption surface area, there was a loss of practically 100% of the module's electrical efficiency.

5. ACKNOWLEDGEMENTS

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