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Experimental study on the effect of tilt angle and dust fouling on the electrical parameters of PV modules in Bambey, Senegal

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A B S T R A C T

Cet article présente une étude expérimentale de l'effet de l'encrassement par la poussière sur la performance électrique des modules PV pour différents angles d'inclinaison dans un environnement semi-aride. Dans cette étude, cinq modules PV sont installés au-dessus du toit à une hauteur de 3,5 m à des inclinaisons de 0°, 15°, 30°, 45° et 60°. La durée d'exposition des modules sans nettoyage est de 6 mois entre octobre et avril. Afin d'analyser les performances des modules PV, le courant de court-circuit et la tension en circuit ouvert ont été mesurés toutes les 5 minutes. Les résultats de cette étude ont montré que la plus grande perte de production d'énergie due à la poussière a été constatée au niveau de l'inclinaison de 15° avec un pourcentage de perte journalière de l'ordre de 46% par rapport à la production de ce même module dans le cas où ce dernier est considéré comme propre.

This article presents an experimental study of the effect of dust fouling on the electrical performance of a PV module for different angles of inclination in a semi-arid and temperate environment. In this study, five PV modules were installed above the roof of a laboratory at a height of 3.5 m at inclinations of 0º, 15º, 30º, 45º and 60º. The exposure time of the modules without cleaning is 6 months between October and April. In order to analyze the performance of the PV modules, the short-circuit current and the open-circuit voltage were measured every 5 minutes. The results in this study showed that the greatest loss of energy production due to dust was noted at the level of the 15º inclination with a percentage of daily loss of the order of 46% compared to the production of this same module in the case where the latter is considered clean.

I. INTRODUCTION

Energy insecurity remains a major concern in the policy of access to energy for all; of sufficient quality and quantity for each stratum of society Mashhoodi and al., 2019, Boemi and al., 2019. The increase in the rate of population without access to necessary and sufficient energy exacerbates the problem and, consequently, the awareness takes a particular rise among the citizens of the whole world Okushima, 2017, Day and al., 2016. As proof of this awareness, the United Nations Development Program (UNDP) has reserved an important place for the issue of access to energy Casillas and al., 2012, Jackson and al., 2018. Among the objectives cited in this program, objective number 7 refers to "clean and inexhaustible energy", with the aim of ensuring access to sufficient, sustainable, reliable and inexpensive energy, in order to alleviate energy insecurity in the world, more particularly in the third world. For these objectives, the use of renewable energy sources remains an essential factor and these sources have proven to be the alternative to fight against the increase in energy poverty and to participate in the sustainability of energy supply Khan and al., 2022, Abdul and al., 2022, Tutak and al., 2022. The specificities and major strengths of renewable energy sources compared to other existing sources are their availability on a large scale, as well as on a small scale Ayamolowo and al., 2022, Diouf and al., 2021; their inexhaustibility Hachicha and al., 2019; them easy accessibility Meried,2021; their cleanliness Oyewo and al., 2019,

Rahman and al., 2022; etc. So that consumers can supply their own energy demand Takase and al., 2022. Autonomous consumption by everyone can be the solution to energy insecurity, since it makes it possible to reduce the cost of energy Mills and al., 2020, Khezri and al., 2022. Among the renewable energy sources, solar energy, more particularly photovoltaic solar energy, offers greater flexibility and adequate adaptation because of its small-scale use and its cost. Its adaptation technology is better in installations in different places close to the user, such as the ground or on the roofs of residences Sun and al., 2022, Behar and al., 2021. But also, its ease of implementation makes it the best-known photovoltaic technology worldwide Joshi and al., 2019, Islami and al., 2021. Recent studies on rooftop photovoltaic potential in Istanbul revealed that out of 39 districts with 1.3 million buildings in use, the total rooftop photovoltaic power generation in Istanbul may have a potential to meet 67% of the total electricity consumption compared to production during the year 2019 Yildirim and al., 2021. Thus, this framework facilitates individual or collective automation Masson and al., 2022 thus contributing to the spatial occupation of technology, to the reduction of greenhouse gas emissions, but above all it facilitates the improvement of energy efficiency and durability Zakeri and al., 2021. According to Tercan and al., 2022, maximizing self-consumption in PV systems is the most effective way to reduce energy poverty in households and remote areas, since self-consumption can reduce the effects of regulations and market prices, electricity on users Roberts and al., 2019, Lee and al., 2020.

In addition, for the locations of PV modules, it is important to study certain factors that affect the optimal functioning of the latter Nfaoui and al., 2020. Among these factors, the optimal inclination angle and orientation angle of the solar modules remain important points for a better production of the PV systems. According to Guo and al., 2017, the optimal orientation angle depends on the hemisphere where the place of study is located. For the northern hemisphere, the optimal orientation is south, while for the southern hemisphere, the optimization is obtained with more northern orientations. Several researches on the determination of optimal tilt angle have been updated in order to draw clear conclusions. Some authors have concluded that the optimal inclination is equal to the latitude of the location for Building Integrated Photovoltaic (BIPV) systems ($\theta opt = |\Phi|$) Cheng and al., 2009. These have proven 98.5% production efficiency over the estimated optimum tilt angle for a latitude range of 0° to 85° in the northern hemisphere. Other authors have found that the optimal angle is equal to the subtraction of 10° from the latitude for the ranges from 36° to 46° ($\theta opt = |\Phi|-10$) Gharakhani and al., 2012, while others multiplied a constant equal to 0.69 at the latitude, then added a constant value equal to 3.7° ($\theta opt = 3.7 + (0.69 \cdot |\Phi|)$) Lorenzo, 2006. Some others, taking into account the accumulation of dust on the surface of the PV modules, added 10° to the latitude before using the same method of calculation as equation 3 ($\theta opt = 3.7 + 0.69 \cdot (|\Phi|+10)$) Perpiñán, 2011. According to Khan and al., 2020, in their study on optimal location and influence of optimal inclination on PV performance, the optimal inclination angles for locations that are on the equator, i.e., the latitude 0°, are between -2.5° and 2.5°. For locations just above the equator, optimum tilt angles are between 5 and 28 for latitude 2.6°−30°N; 29° to 40° for latitude 40°−70°N and 41° to 45° for latitude 71°−90°N. For locations at 2.6°−30°S, the optimum tilt angles are between -4° and -32°; for 30°−46°S, it is -33° to -36°; for 47°−65°S it is -34° to -50° and for 66°−90°S it is -51° to -62°. The results of the work done by Abdallah and al., 2020 showed that adjustments of the angles of inclination of solar modules in certain parts of Palestinian cities can generate about 15% to 17% more solar energy than the case of solar modules fixed on a horizontal surface.

The variation of the angle of inclination can also affect dust deposit on the surface of the PV modules. Work has already been carried out in experiment or simulation taking into account the effect of fouling, glass material, temperature on the location of the optimum tilt angle. Therefore, the estimation of production losses due to dust accumulation on the variation of the tilt angle is essential to assess the economic feasibility and the production capacity of a PV system. Varying the angle of inclination of the modules can lead to an increase or a decrease in the rate of dust accumulation, thus creating considerable production losses Ullah and al., 2019, Babatunde and al., 2018, Said and al., 2014. For angles of 0º, 15º, 30º, 45º, the energy generated by PV modules is reduced by 58.2%, 27.8%, 21.7% and 20.7%, respectively Khodakaram and al., 2020.

The objective of this article is to analyze the electrical performance of PV modules as a function of different tilt angles and dust accumulation, providing a range of tilt angles that optimizes production and listing production loss rate due to fouling. A bad inclination of the PV module can lead to the accumulation of dust and therefore impact the amount of energy generated by the latter. However, representations of these effects on energy yield and PV system performance are generally based on theoretical calculations, while there is a lack of experimental investigation. Therefore, an experimental device is installed on a roof of University Alioune Diop of Bambey in order to make an experimental study of the problem. This article aims to study the optimal angle(s) of a clean module and it estimates the percentages of current and voltage losses caused by dust as a function of the same variations in the angle of inclination of the modules.

II. MATERIALS AND METHODS

II.1. Experimental site and PV modules used

The experimental study was performed at Alioune Diop University in Bambey, Senegal. The geographical location of this place is 14º41'51.71 "North and 16 ° 28'44.5" West and it is on the south side and roughly on the national road Nº3. The photovoltaic system is composed of 5 monocrystalline silicon photovoltaic modules of 10 Wp mounted on a 3.5 m high roof (see Figure 1). The angles of inclination are 0º, 15º, 30º, 45º and 60º and the orientation is set south. Table 1 shows the specifications of the PV modules.

Table 1. Electrical characteristics

Settings	Values
Maximum power	10 W
Short circuit current	0.51 A
Open circuit voltage	26 V
Current at maximum power point	0.47 A
Voltage at maximum power point	21.2 V

II.2. Measuring system

The short-circuit current and open- circuit voltage data of the five modules are measured directly using two Mu58A type multimeters which have the following specifications: the voltage measurement range is 200 mV to 1000 V with an uncertainty of ±0.5% and the current measurement range is 20 µA to 20 A with an uncertainty of ± 0.8%. To realize all measurements, all the data are determined simultaneously daily every 5 minutes from 9:00 a.m. (UTC) to 5:00 p.m. (UTC). The set of data obtained over 6 months of exposure of the PV module is transformed into daily average data. The electrical parameters such as the Voc and the Isc are then extracted and analyzed.

Fig. 1. Experimental PV groups

Fig.2. Proposed tilt angles of experimental system

Figure 3 illustrates the schematic of the measuring system by digital multimeter.

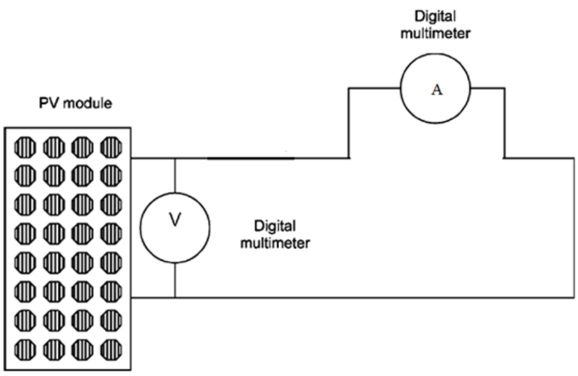

Fig.3. Schematic circuit diagram of PV module measurement system

III. RESULTS AND DISCUSSIONS

III.1. Output voltage variations with tilt angle and soiling

The results obtained are presented as a daily average in Table 2. They are also presented as a percentage in relation to the open-circuit voltage at STC of the PV solar modules. The associated voltage is equal to 26 V.

Table 2. Photovoltaic output voltage variation with tilt angle and soiling

θ (degree)	0°	15°	30°	45°	60°
Output voltage for clean module	24.49	23.93	24.35	24.49	24.24
% of maximum voltage	94.20	92.03	93.67	94.17	93.22
Output voltage for dusty module	24.22	23.32	23.89	23.96	23.73
% of maximum voltage	93.14	89.69	91.88	92.14	91.27

The highest PV voltage output was obtained at 0° and at 45°. While the lowest PV voltage output was seen at a tilt angle of 15°. However, it should be noted that the angle of inclination and fouling do not have a great influence on the performance of PV modules, since the latter operate, for the most part, at 90% of their nominal operation. This is always the case because then temperature has a negative effect on the voltage Paudyal and al., 2021, Zaraket and al., 2019, and the PV module can never operate at its nominal voltage taken at standard test condition (STC). All of this can be viewed in the histograms shown in Figure 4.

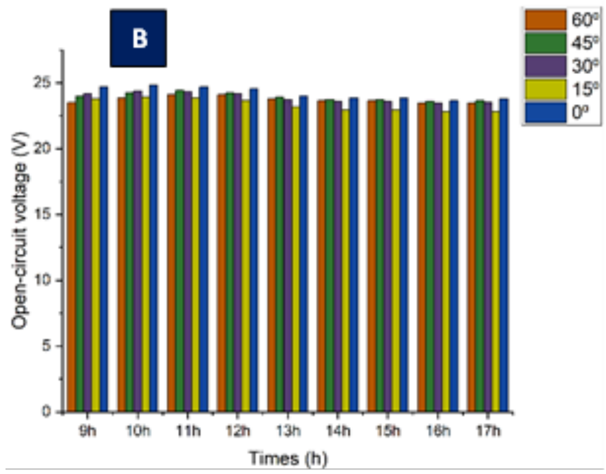

Fig.4. Daily mean voltage variation at different tilt angle: (A) clean module; (B) dusty module

III.2. Output current variations with tilt angle and soiling

The daily average experimental data of the short-circuit current for different tilt angle in clean and dusty PV module are presented in Table 3. They are also presented as a percentage compared to the short-circuit current at STC of the PV module. This current value, given by the manufacturer, is equal to 0.51 A.

Table 3. Photovoltaic output current variation with tilt angle and soiling

θ (degree)	0°	15°	30°	45°	60°
Output current for clean module,	0.397	0.393	0.357	0.315	0.231
% of maximum current	77.81	77.12	69.97	61.77	45.28
Output current for dusty module,	0.16	0.20	0.224	0.222	0.291
% of maximum current	56.97	43.5	43.83	39.65	30.83

It is evident from Table 3 that the short-circuit current decreased very significantly, compared to the voltage. These percentage differences show that the angle of inclination is a key parameter that influences the PV energy production and more particularly the output current of PV modules. It should be noted that for better material efficiency, the coverage of PV modules has been improved based on plasmonic, which increase the absorption in PV modules due to the considerable reduction in the physical thickness of the absorber layers Atwater and al., 2010. However, the ratings of PV modules are generally tested under standard conditions that involve perpendicular incident light, although the real angles of incidence differ from perpendicular to the PV panel surface, resulting in a decrease in the real performance of the PV module due to the reflection effect mainly induced by the air-glass interface. Therefore, if the optimum tilt angle of the module is not achieved, multiple reflections and a reduction in the capture surface of the sun's rays must be expected on the glass surface of the module. Given that the main factor influencing the current intensity of PV modules is the incoming solar irradiation, then multiple reflections and the reduction of the capture surface of the latter can only degrade this intensity (see Fig.5. A.). Due to dust deposition resulting from prolonged exposure without cleaning, as shown in Figure 5.B., we observe that the slightly inclined modules (0° and 15°) have a better production, compared to the others. Dust deposition has a serious impact on transmittance, thus participating in the degradation of energy produced by PV cells. We can conclude that the reduction in transmittance is greatly affected by dust deposition density and reduction percentage improves with exposure duration and inclination angle increment.

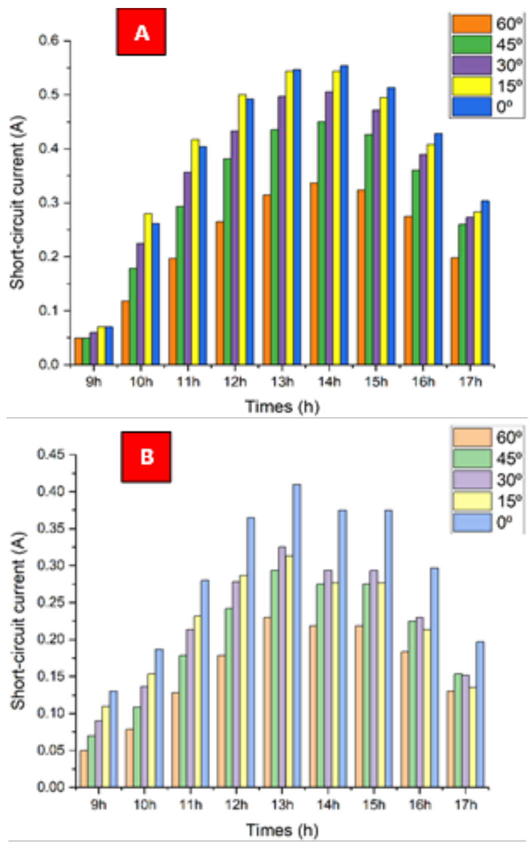

Fig.5. Daily mean current variation at different tilt angle: (A) clean module; (B) dusty module

For a better insight into the effect of dust, a specific study was made. Figure 6 shows, on a histogram, the percentages of current loss that are caused by the dust accumulation. These percentages were calculated in relation to the production of each module in its own case. Analysis of this curve reveals that the tilted modulus a 15º encompasses more production losses, with one at around 45.99%. The smallest percentage of loss is noted at the level of the PV module inclined at 0º. It should be understood that the optimal angle of inclination of our location is between 14º and 15º. However, it was to be expected that we have more impact because, at azimuth time, the solar rays come perpendicularly on the glass surface of the PV module. Consequently, these rays will be reflected for the most part by the dust particles, resulting in excess losses. Now for the angles of 30º, 45º and 60º, we notice a slight decrease in the losses which are caused by the rate of variation of the deposited dust which is a function of the variation of the tilt angle, with losses of 39.38%, 37.58% and 32.95%, respectively. The lowest loss is at tilt 0º and it is approximately 29.38%. Here we can simply say, compared to case 15º, that the reflection phenomena caused specifically by dust are less. Indeed, the light rays that arrive at the PV module are not totally perpendicular to the latter, so most of these rays will be transmitted directly to the PV cells. From where we can expect low attenuation therefore a better production of energy among the others.

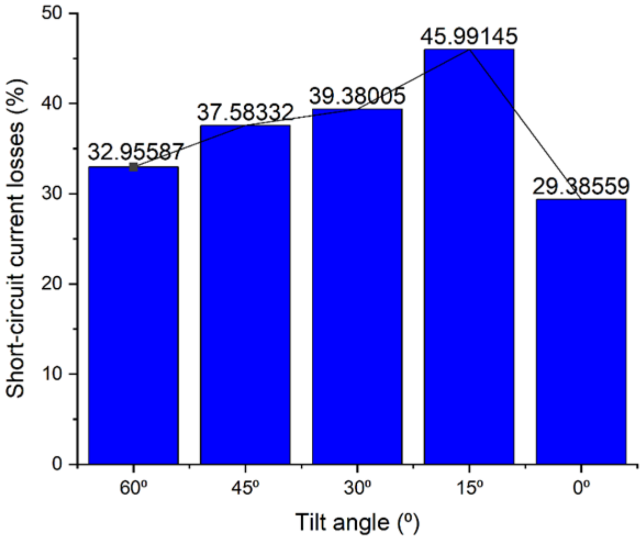

Fig.6. Effect of dust on short-circuit current at different tilt angle

VI. CONCLUSION

This article discusses the electrical performance of monocrystalline silicon PV module at tilt angles of 0°, 15°, 30°, 45°, 60° and the effect of dust deposition at the University of Bambey, Senegal. Tilt angle adjustments, to find the optimal value, play an important role in maximizing the energy received by the PV module and the power generation. The tension of the modules is not too affected by the variation in inclination. We noted that the optimal tilts angles found (0° and 15°), one of them equals to the latitude of the place of the experiment which is 15°. The results showed that the optimal tilt angle is equal to 15° between 9 a.m. and 12 p.m. and 0° between 1 p.m. and 5 p.m. for a clean module.

The deposit of dust is more intense on the plates inclined 0° and 15° after 6 months of exposure. The reduction in transmittance is strongly affected by dust with 45.99% loss of short-circuit current for the angle of 15° (equivalent to the latitude of the place of location: possibility of multiple reflections of the solar rays by the particles of dust). The voltage is slightly degraded by dust. The combined effect of angle of inclination and dust deposition can still lead to excess energy losses and this was more visible when the module is tilted at 15°, in compliance with the standards established in Senegal.

The electricity production and the life cycle cost of a PV system must be compared to determine the reliability and feasibility of the latter. The methodology used in this work can be a good source of inspiration for previous annual and large-scale study.

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