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Impact of dust on the photovoltaic (PV) modules characteristics after an exposition year in Sahelian environment: The case of Senegal

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The objective of this paper is to find the effect of dust on the performance of photovoltaic modules. To this end, the International Center for Research and Training in solar energy at Dakar University and the Lasquo-ISTIA Laboratory of Angers University have put in place a research project in order to investigate the impact of Sahelian climatic conditions on the photovoltaic (PV) modules characteristics. Accordingly, monocrystalline silicon (mc-Si) PV module and a silicon polycrystalline (pc-Si) PV module are installed at Dakar University and monitored during one operation year without cleaning. We evaluate the variation depending on the dust of electrical characteristics such as I-V and P-V curves, open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum ouput current (I_{max}), maximum output voltage (V_{max}), maximum power output (P_{max}) and fill factor (FF). This work has highlighted the impact of dust on the Current-Voltage (I-V) and Power-Voltage (P-V) characteristics of PV modules (mc-Si and pc-Si) with the advent of the mismatch effect. P_{max}, I_{max}, I_{sc} and FF are the most affected performance characteristics by the dust deposits on the PV modules surface. The maximum power output (P_{max}) loss can be from 18 to 78% respectively for the polycrystalline module (pc-Si) and monocrystalline module (mc-si). I_{max} loss can vary from 23 to 80% for respectively pc-Si and mc-Si modules. However, the maximum voltage output (V_{max}) and the open-circuit voltage (V_{oc}) are not affected by dust accumulation for both technologies studied. The fill factor (FF) may decrease from 2% for the pc-Si module to 17% for the mc-Si module.

Key words: Photovoltaic module, photovoltaic (PV) module performance parameters, dust effect.

INTRODUCTION

Using the locally available renewable energy sources, especially solar irradiation which is of high availability all over the globe, offers a strategic solution for power supply problems. It is important to implement the photovoltaic system technology suitable for the relevant locations in order to take into consideration the local environment aspects and optimize the energy yield. However, one of the constraints of photovoltaic (PV) systems in the Sahelian areas is related to the dust deposition on the photovoltaic modules surface. The accumulation of dust particles on the surface of PV module greatly affects its performance especially in the

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desert areas. But desert countries are of course best suited to photovoltaic power generation due to abundant availability of sunlight throughout the year. Nowadays the idea for setting up vast solar arrays in Sahelian countries and exporting the power to other countries are being discussed. In a bigger PV solar plants, more work force and machines will be needed to keep making the rounds and cleaning the panels, especially after a sand storm. The dust accumulation on the PV panel surface depends on different parameters like PV panel inclination, kind of installation (stand alone or on tracker), humidity etc. Many research results discuss about performance of panel with dust concentration on the surface. Hottel and Woertz were amongst the pioneers investigating the impact of dust on solar systems (Hottel and Woertz, 1942). They recorded a maximum degradation in collector performance of 4.7%, with an average loss in incident solar radiation being less than 1%. In a study (Salim et al., 1988) into dust accumulation on a solar-village PV system near Riyadh indicated a 32% reduction in performance after eight months. In Wakim (1981) is indicated a reduction in PV power by 17% due to sand accumulation on panels in Kuwait city after six days. Furthermore the study also indicated that the influence of dust on PV performance would be higher in spring and summer than in autumn and winter. In a different study on the effects of dust on solar PV panel in Palo Alto, California (Katz, 2011), it was reported that the dust on solar PV panels caused a 2% of current reduction relative to that for clean panels. In Shaharin (2011), the reduction in the peak power generated by the dust on the PV panel can be up to 18%. The power loss due to soiling is therefore a function of the type of dust, the length of time since the last rainfall and the cleaning schedule (Kymakis et al., 2009). In general, the standard industry assumption of soiling losses ranges from 1 to 4% on an annual basis (Detrick et al., 2005). In areas of frequent rainfall, it was demonstrated that the rain could clean the PV modules to an extent of restoring the performance to within 1% of full power (Hammond et al., 1997). Accordingly, in a more recent soiling analysis performed in Crete, with climatic conditions almost identical to Cyprus, the annual soiling loss was 5.86%, with the winter losses being 4 to 5 and 6 to 7% in the summer (Kymakis et al., 2009; Sharma and Bowden, 2012). A soiling investigation was carried out also for the systems installed in Egypt and specifically by comparing the energy produced by a clean module, a module that has been exposed to dust for a period of one year and a module that has been exposed to dust but cleaned every two months. The energy production results showed that the ‘one year dusty module’ produced 35% lower energy while the ‘two month dusty module’ produced 25% lower energy compared to the clean module (Ibrahim et al., 2009). In Catelani et al. (2012), it claimed that the dust lead to a decrease of the transmittance of solar cell glazing and cause a significant degradation of solar conversion efficiency of PV modules. Same technology PV panel from different manufacturers suffers in completely different pattern. For a common PV user it is important to know how frequent the panel has to be cleaned. In case if the frequent cleaning is not feasible, it is important to know the performance loss due to dust for additional estimation to compensate the loss. The study on effect of dust on the PV panel will help to select panel technology for particular type of application and location. Thus, this work was initiated to study the influence of dust deposits on the electrical performance of photovoltaic modules in the long term (Zhou et al., 2007). Current-Voltage (I-V) and Power-Voltage (P-V) curves, open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (FF) and maximum power (P_{max}). The photovoltaic test fields at Dakar University in Senegal is shown in Figure 1. On this figure is shown the dust layer accumulated on the surface of PV modules after one exposition year without cleaning on the site of Dakar in Senegal.

MATERIALS AND METHODS

Presentation of photovoltaic test field

The photovoltaic platform shown in Figure 1 is used in this study. It is installed at the Higher Polytechnic School of the Dakar University, Senegal. Senegal is located on the extreme western Africa between 12.5° and 16.5° North latitude and 12° and 17° West longitude. It presents a dry tropical climate characterized by two seasons: A dry season from November to June and a rainy season from July to October (ANAMS, 2012). Senegal has a significant solar potential with annual average radiation duration of about 3000 h and an exposure rate of 5.7 kWh/m^2/day. This radiation varies between the northern part more sunlit (5.8 kWh/m^2/day in Dakar) and the southern part richest in terms of precipitation (4.3 kWh/m^2/day in Ziguinchor) (PSA, 2011). The temperature varies from 16°C around Dakar (January) to 38°C in the South (October). The rainfall increases from North to South with an annual average of 300 mm in the extreme North and 1500 mm in the extreme South (ANAMS, 2012). The relative humidity varies between 75 and 95% (Wofrance, 2012). The platform is installed in Dakar between 17.28° West longitude and 14.43° North latitude to 31 m altitude.

Platform has been made operational since one year. It consists of one monocrystalline (A) and one polycrystalline (B) photovoltaic modules. The technical characteristics of PV modules provided by the manufacturers are given in Table 1. The modules have operated during one year without being cleaned inducing the deposition of a dust layer on the modules surface as shown in Figure 1. Thus, in this state (one year from dust) performance parameters (I-V and P-V curves, V_{oc}, I_{sc}, FF and P_{max}) are measured under the standard test conditions (AM1.5, 1000 W/m^2, 25°C). Then the same process is repeated on the same properly cleaned (without any trace of dust on their surface) under the same standard conditions of test modules as previously. These measurements are made with the test instrument of PV modules known as "IV 400".

Presentation of measurement instrument "I-V 400"

"I-V 400" carries out the field measurement of the I-V characteristic and of the main characteristic parameters both of a single module and of module strings. The instrument measures, together with I-V characteristic of the device being tested, also the values of its

Figure 1. Photovoltaic test field at Dakar University in Senegal.

Table 1. Technical characteristics of PV modules.

Module	Technology	Manufacturer	Reference	Parameter	Value
A	Monocrystalline Silicon	Bosch	SP36-145M	Maximum output power (Pmax)	145 W
				Maximum output voltage (Vmax)	17.9 V
				Maximum output current (Imax)	8.1 A
				Open circuit voltage (Voc)	22.7 V
				Short-circuit current (Isc)	8.5 A
				Fill factor (FF)	75.14%
B	Polycrystalline Silicon	Aleo	S18-230	Maximum output power (Pmax)	230 W
				Maximum output voltage (Vmax)	29.2 V
				Maximum output current (Imax)	7.88 A
				Open circuit voltage (Voc)	36.6 V
				Short-circuit current (Isc)	8.44 A
				Fill factor (FF)	74.48%

temperature and incident irradiation. The acquired data are then processed to extrapolate the I-V characteristic at standard test conditions (STC) in order to proceed with the comparison with the nominal data declared by the modules manufacturer, thus immediately determining whether or not the string or the module being tested respects the characteristics declared by the manufacturer. Output current or voltage from the module is measured with the 4-terminal method, which allows extending the measurement cables without requiring any compensation for their resistance, thus always providing accurate and precise measures. Measurement of output voltage from module is up to 1000V DC. Measurement of output current from module is up to 10A DC. Measurement of solar irradiation (W/m^2) is carries out with reference cell. Measurement of output DC and nominal power from module is performed. Numerical and graphical display of I-V curve is available. It Measures the module fill factor. Mechanical inclinometer is integrated for the detection of the incidence angle of solar irradiation. Electrical specifications of "IV 400" are given in Table 2.

We note that accuracy parameter is calculated as ±[% reading + (number of dgts) x resolution] at 23±5°C, <80%HR (Datasheet I-V 400, 2012).

Investigating parameters

The most important electrical characteristics of a PV module are the I-V and P-V curves, short-circuit current I_{sc}, open-circuit voltage V_{oc}, the fill factor FF and the maximum power output P_{max}. They are defined and modeled as follows.

The I-V and P-V curves

The I-V (current-voltage) curve of a PV string (or module) describes its energy conversion capability at the existing conditions of irradiance (light level) and temperature. Conceptually, the curve represents the combinations of current and voltage at which the string could be operated or 'loaded', if the irradiance and cell temperature could be held constant. Figure 2 shows a typical I-V curve, the power-voltage or P-V curve that is computed from it, and key points on these curves. Referring to Figure 2, the span of the I-V curve ranges from the short circuit current (I_{sc}) at zero volts, to zero current at the open circuit voltage (V_{oc}). At the 'knee' of a normal I-V curve is the maximum power point (I_{mp}, V_{mp}), the point at which the array generates maximum electrical power. In an

Table 2. Electrical specifications of "I-V 400".

Parameter	Range	Accuracy	Resolution
Voltage (Vdc)	5.0 ÷ 999.9	0.1	±(1.0%rdg+2dgt)
Current (Idc)	0.10 ÷10.00	0.01	±(1.0%rdg+2dgt)
Power maximal (Wdc)	50 ÷ 9999	1	±(1.0%rdg+6dgt)
Irradiation (mVdc)	1.0 ÷ 100.0	0.1	±(1.0%rdg+5dgt)
Temperature (℃)	-20.0 ÷100.0	0.1	±(1.0%rdg+1℃)

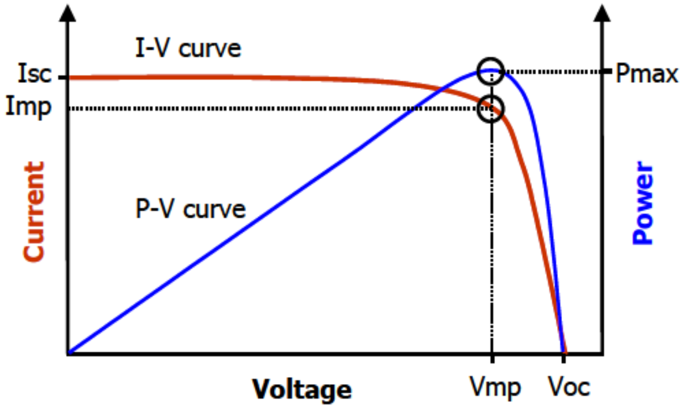


Figure 2. The I-V and P-V curves of a photovoltaic module.

operating PV system, one of the jobs of the inverter is to constantly adjust the load, seeking out the particular point on the I-V curve at which the array as a whole yields the greatest DC power. At voltages well below V_{mp}, the flow of solar-generated electrical charge to the external load is relatively independent of output voltage. Near the knee of the curve, this behavior starts to change. As the voltage increases further, an increasing percentage of the charges recombine within the solar cells rather than flowing out through the load. At V_{oc}, all of the charges recombine internally. The maximum power point, located at the knee of the curve, is the (I,V) point at which the product of current and voltage reaches its maximum value.

The short circuit current I_{sc}

At normal levels of solar irradiance, the short-circuit current can be considered equivalent to the photocurrent I_{ph}, that is, proportional to the solar irradiance G (W/m^2). But this may result in some deviation from the experimental result, so a power law having exponent a is introduced in this paper to account for the non-linear effect that the photocurrent depends on. The short-circuit current I_{sc} of the PV modules is not strongly temperature dependent. It tends to increase slightly with increase of the module temperature. For the purposes of PV module performance, modeling this variation can be considered negligible. Then, the short-circuit current I_{sc} can be simply calculated by:

$$I_{sc} = I_{sc0}\left(\frac{G}{G_0}\right)^{a} \tag{1}$$

Where I_{sc0} is the short-circuit current of the PV module under the standard solar irradiance G_0; while I_{sc} is the short-circuit current of the PV module under the solar irradiance G; a is the exponent responsible for all the non-linear effects that the photocurrent depends on.

The open-circuit voltage V_{oc}

The relationship of the open-circuit voltage to irradiance is known to follow a logarithmic function based on an ideal diode equation, and the effect of temperature is due to the exponential increase in the saturation current with an increase in temperature (Luis and Sylvestre, 2002). This conclusion causes some difficulties in replicating the observed behaviours of the tested PV modules. Additional terms or some amendatory parameters must be introduced to account for the shunt resistance, series resistance and the non-ideality of the diode. Based on the model given by Van Dyk et al. (2002) and then take into account the effect of temperature, the open-circuit voltage Voc at any given conditions can be expressed by:

$$V_{oc} = \frac{V_{oc0}}{1+b\,ln\frac{G_0}{G}}\left(\frac{T_0}{T}\right)^{\gamma} \tag{2}$$

Where V_{oc} and V_{oc0} are the open-circuit voltage of the PV module under the normal solar irradiance G and the standard solar irradiance G_0; b is a PV module technology specific related dimensionless coefficient (Van Dynk et al., 2002); and γ is the exponent considering all the non-linear temperature–voltage effects.

The maximum power output P_{max}

The photovoltaic module performance is highly affected by the solar irradiance and the PV module temperature. In this paper, we consider a simplified model maximum power-output of PV module to estimate its performance (Ould Bilal et al., 2012). It is given by Equation 3.

$$P_{max} = V_{oc}.I_{sc}.FF \tag{3}$$

Where I_{sc} and V_{oc} are the short-circuit current and open-circuit voltage of solar photovoltaic module (Omer, 2008), FF (dimensionless) is the fill factor. It is the ratio between the nominal and maximum power standard (Koutroulis et al., 2006).

The fill factor FF

The fill factor (FF) of a PV module or string is an important performance indicator. It represents the square-ness (or 'rectangularity') of the I-V curve, and is the ratio of two areas defined by the I-V curve, as illustrated in Figure 3. Although physically unrealizable, an ideal PV module technology would produce a perfectly rectangular I-V curve in which the maximum power point coincided with (I_{sc}, V_{oc}), for a fill factor of 1. The fill factor is important because if the I-V curves of two individual PV modules have the same values of I_{sc} and V_{oc}, the array with the higher fill factor (squarer I-V curve) will produce more power. Also, any impairment that reduces the fill factor will reduce the output power. The fill factor can be expressed by:

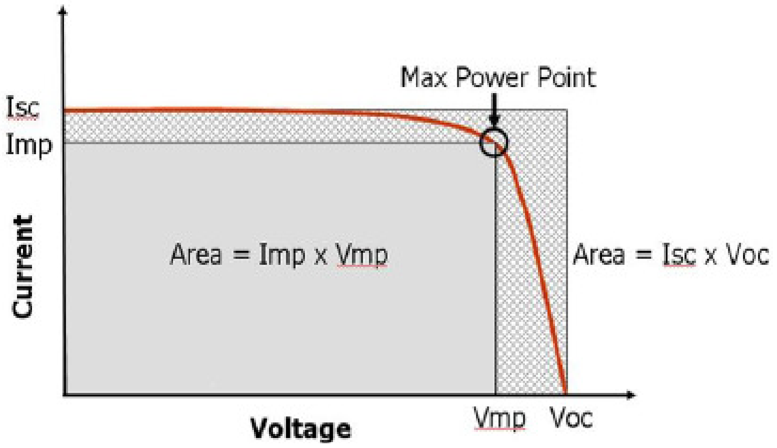
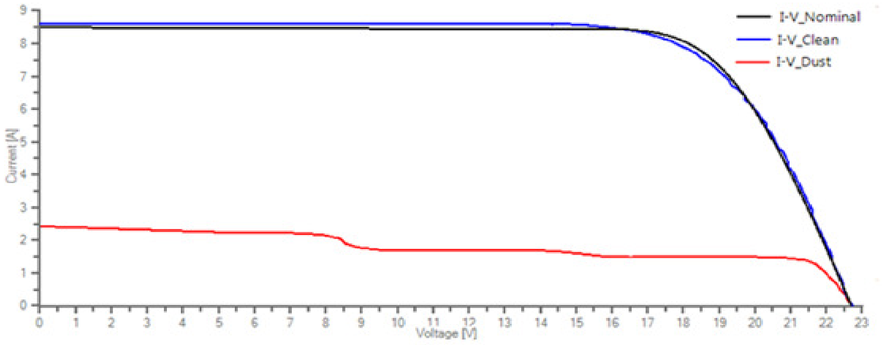
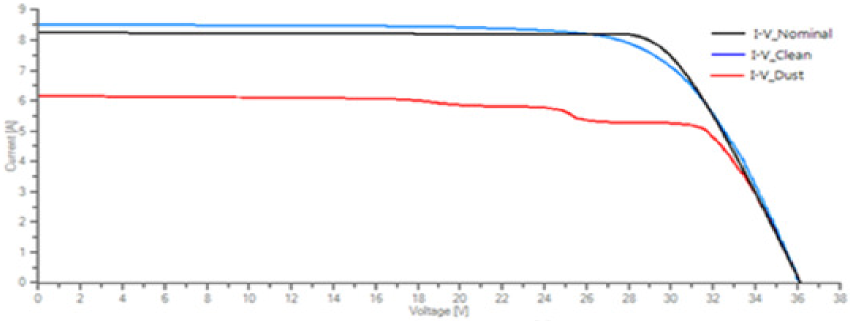


Figure 3. The fill factor, defined as the gray area divided by the cross-hatched area.



a-Monocrystalline PV module



b-Polycrystalline PV module

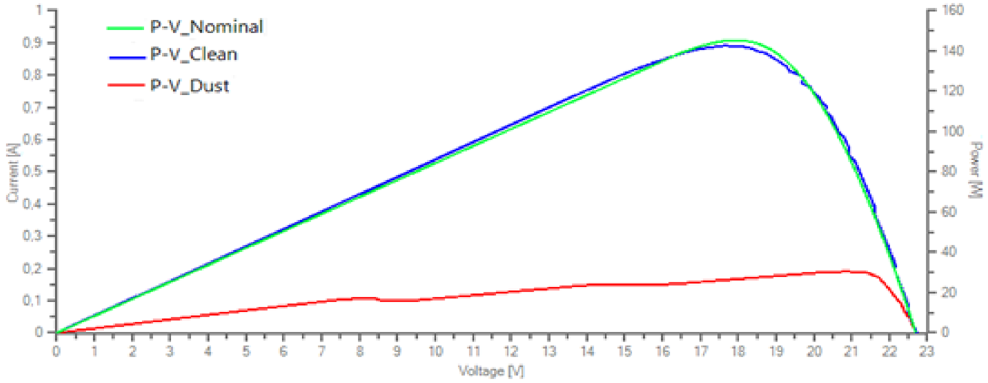
Figure 4. Comparison between the I-V characteristics of PV modules under clean and dusty conditions after one exposition year.

$$FF = \frac{Imp.Vmp}{Isc.Voc} \qquad (4)$$

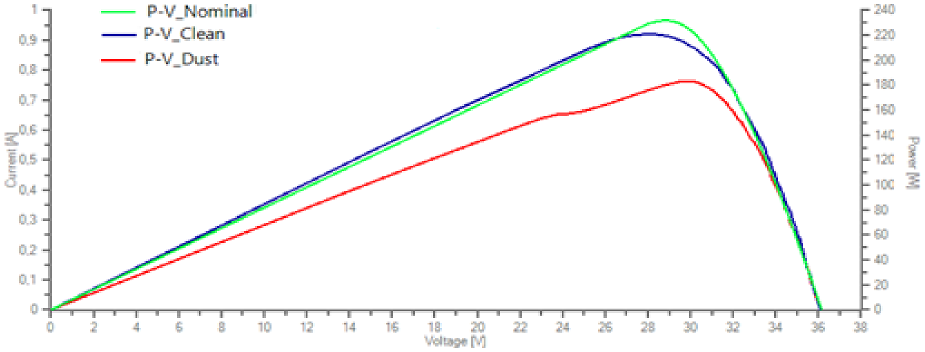
RESULTS AND DISCUSSION

Effect of dust on I-V and P-V characteristics

All tests are performed in the standard test conditions (STC) corresponding to AM 1.5, 25°C and 1000 W/m^2. Shown in Figures 4 and 5 are respectively the current-voltage (I-V) and power-voltage (P-V) curves for PV modules in three conditions: Nominal conditions, PV module clean and PV module dusty for monocrystalline silicon (a) polycrystalline silicon (b) technologies. The I-V and P-V characteristics corresponding to the nominal conditions and clean PV modules clearly present a normal form for both technologies. It may be noted that the curves corresponding to the I-V and P-V modules



a-Monocrystalline PV module



b-Polycrystalline PV module

Figure 5. Comparison between the P-V characteristics of PV modules under clean and dusty conditions after one exposition year.

clean after a exposition year are almost confounded with nominal curves for the two technologies. However, a small difference is noted at the short-circuit current (I_{sc}) and maximum current (I_{max}) for the IV characteristic whereas the open-circuit voltage (V_{oc}) shows no significant variation. For the P-V characteristics, a decrease of the maximum power (P_{max}) after one exposition year was noted on the two technologies. These variations in I_{sc}, I_{max} and P_{max} on clean modules after one year of operation reveal a modules degradation probably due to other parameters such as temperature, humidity, UV. The performance of PV modules varies according to the climatic conditions and gradually deteriorates through the years (Sanchez-Friera et al., 2011; Osterwald et al., 2006; Adelstein and Sekulic, 2005; Dunlop and Halton, 2005; Cereghetti et al., 2003). On the other hand, the I-V and P-V characteristics of monocrystalline and polycrystalline PV modules after one exposition year under the natural dust without cleaning are heavily modified. The characteristics I_{sc}, V_{max} and P_{max} present very significant decreases that are evaluated subsequently. The distortion and mismatch recorded on the I-V and P-V curves are due to the dust on the surface of the modules. Indeed, dust induces generally nonuniform shading on the PV modules surface and thereby chains of PV cells are not illuminated with the same intensity. Therefore they do not have the same behavior and characteristics I-V and P-V of modules become modified. The nonuniform shading of the PV module will induce a mismatch effect observed on the I-V and P-V characteristics as shown in Figures 4 and 5 (Mohammadmehdi et al., 2013). Following is devotion to the evaluation of the impact of dust on the PV module characteristics such as: Open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum ouput curreent (I_{max}), maximum output voltage (V_{max}), maximum power output (P_{max}) and fill factor (FF).

Effect of dust on I_{sc}, V_{oc}, P_{max} and FF characteristics

Previously, the impact of dust on the I-V and P-V characteristics of PV modules after one exposion year under Sahelian conditions without cleaning was highlighted. Here, we evaluate the impact of dust after one exposition year on open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum ouput curreent (I_{max}), maximum output voltage (V_{max}), maximum power output (P_{max}) and fill factor (FF) of monocrystalline and polycrystalline PV modules. Table 3 summarizes the

Table 3. A summary of the PV module parameters variation observed after one exposition year (clean and dusty).

Modules	Parameter	Initial value	Clean module after one exposition year	Dusty module after one exposition year	Difference absolute	Difference relative (%)
Monocrystalline PV module	Pmax (W)	145	144.59	32.17	-112.42	-77.75
	Vmax (V)	17.9	17.83	20.79	2.96	16.60
	Imax (A)	8.1	8.06	1.57	-6.49	-80.52
	Voc (V)	22.7	22.7	22.7	0.00	0.00
	Isc (A)	8.5	8.47	2.09	-6.38	-75.32
	FF (%)	75.14	73.64	60.4	-0.13	-17.98
Polycrystalline PV module	Pmax (W)	230	217.37	178.19	-39.18	-18.02
	Vmax (V)	29.2	28.04	30.09	2.05	7.31
	Imax (A)	7.88	7.75	5.93	-1.82	-23.48
	Voc (V)	36.6	36.16	36.16	0.00	0.00
	Isc (A)	8.44	8.33	6.61	-1.72	-20.65
	FF (%)	74.48	72.09	70.64	-0.01	-2.01

characteristic variations (V_{oc}, I_{sc}, $I_{max,}$ $V_{max,}$ P_{max} and FF) induced by the dust deposition on the PV modules surface. All tests are performed in the standard test conditions (STC). To assess the impact of dust on the performance characteristics of PV modules we calculate the absolute and relative difference between the case where the modules were not cleaned after an exposition year under Sahelian environment and the case where they are cleaned after one operation year under the same environment. Dust deposition on the modules decreases strongly the maximum power for both technologies. The maximum power output (P_{max}) loss can be from 18 to 78%, respectively for the polycrystalline module (pc-Si) and monocrystalline module (mc-si).

Studies carried out in Egypt have shown that this decrease of P_{max} due by the dust could reach 35% after only two months without cleaning PV modules (Ibrahim et al., 2009). The test results on two PV modules technologies reported in Table 3 have also shown that short-circuit current (I_{sc}), maximum output current (I_{max}) and fill factor (FF) are affected by the dust deposits on the PV modules surface. Indeed, we find that the decrease of I_{max} relative to clean modules may vary from 23 to 80% for respectively pc-Si and mc-Si modules. The fill factor (FF) may decrease from 2% for the pc-Si module to 17% for the mc-Si module. However, the maximum voltage output (V_{max}) and the open-circuit voltage (V_{oc}) are not affected by dust accumulation for both technologies studied. All values given in Table 3 are related to the standard test conditions (AM 1.5, 25℃, 1000 W/.m^2).

Conclusion

The effect of the presence of dust on the photovoltaic module surface was studied under Sahelian environment. Two PV modules technologies (monocrystalline and polycrystalline silicon) were exposed during one year on the site of Dakar University in Senegal. Dust has an effect on the parameters performance of photovoltaic modules. The impact of dust on the I-V and P-V characteristics of PV modules after an exposition year under Sahelian conditions without cleaning was highlighted. In the study, it was also shown that the relative differences of PV module performance parameters between the case where the modules were not cleaned after an exposition year under Sahelian environment and the case where they are cleaned after one operation year under the same environment are generally very high. P_{max}, I_{max}, I_{sc} and FF are the most affected performance characteristics by the dust deposits on the PV modules surface. The maximum power output (P_{max}) loss can be from 18 to 78% respectively for the polycrystalline module (pc-Si) and monocrystalline module (mc-si). I_{max} loss can vary from 23 to 80% for respectively pc-Si and mc-Si modules. However, the maximum voltage output (V_{max}) and the open-circuit voltage (V_{oc}) are not affected by dust accumulation for both technologies studied. The fill factor (FF) may decrease from 2% for the pc-Si module to 17% for the mc-Si module. In perspective, we will work with many more PV modules from different manufacturers over a longer duration. This project also aims to measure the amounts of dust deposited on the modules of different technologies in order to investigate on the best adapted technologies to Sahelian environment. We can already say that the cleaning of PV modules exposed in a Sahelian environment must be integrated into a plan of periodic preventive maintenance.

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