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Energy Procedia 74 (2015) 1370 – 1380

Energy Procedia

International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES15

Photovoltaic Platform for Investigating PV Module Degradation

Ababacar Ndiaye[a,b,*], Cheikh M. F. Kébé[b], Abdérafi Charki[c], Vincent Sambou[b], Papa A. Ndiaye[b]

[a] Université Assane Seck de Ziguinchor, UFR – Sciences et Technologies, Département de Physique
BP 523 Ziguinchor, Sénégal.
[b] Centre International de Formation et de Recherche en Energie Solaire (CIFRES)
Ecole Supérieure Polytechnique-UCAD, BP 5085 Dakar-Fann, Sénégal
[c] Université d'Angers-ISTIA-LARIS, 62 Avenue Notre Dame du Lac 49000 Angers, France

Abstract

Photovoltaic research is oriented more and further towards study on PV modules degradation. The objective is to understand the different degradation modes of PV modules and associated factors. This paper presents a platform for measures dedicated to do a study related to degradation of electrical characteristics of the photovoltaic modules. It is installed on the site at University of Dakar in Senegal. This work proposes a method for standardization of the direct measures of the short-circuit current (Isc) and the open-circuit voltage (Voc) of PV modules. The approach used for the assessment of degradation of Isc and Voc involves a comparison between baseline values given by manufacturer and those measured in real operating conditions brought back in the standard test conditions (STC). Findings presented on degradation of Isc and Voc photovoltaic modules cover the first ten months of measurements from Mars to January. Degradation of short-circuit current is about 13% for the three days. The degradation of open-circuit voltage measured during the three days is 8%.

Peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)

Keywords: PV module, degradation, standard test conditions.

1. Introduction

Energy remains a key element for socio-economic development of a society. It becomes more problematic with soaring oil prices on the one hand and the environmental consequences of using fossil fuels on the other. Today, different forms of renewable energy in various technologies offer greater flexibility and reliability satisfactory to reduce the energy deficit caused by the growth of the demand. Photovoltaic energy now occupies an important position in the renewable energy market. Indeed, solar energy is used to satisfy the needs for industries, households,

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doi:10.1016/j.egypro.2015.07.783

and individuals. Over the previous decades, the photovoltaic (PV) market has recorded unprecedented growth. In particular during the last year, the photovoltaic market has reached a cumulative installed capacity of roughly 40 GW world-wide, with an annual added capacity of 16.6 GW [1]. Need for a reasonable energy for an individual or an industrialist, a PV system can be effective provided that the installation is optimized and maintained. For this, it is important to understand the reliability and lifetime of such systems. The Investors' demand is being more and more clearly answered in regard to reliability and especially the lifetime of solar systems for the analysis of their technical and financial facilities. Monitoring degradation of a PV system is just as important as a high degradation rate translates directly into a loss of power output; hence a reduction in the return on investment [2] .The lack of precised information on the rate of degradation increases the financial risk [3] . Reliability and lifetime of photovoltaic system depend mainly on the energy performance of modules and their different modes of degradation. Information on the degradation of modules is available since the early 1970 [4] . According to the literature, results from experimental trials are given. Different techniques and testing methods are used. These results obtained for most laboratory tests are not always accurate and consistent on the degradation rates of PV modules announced. In 2002, the National Renewable Energy Laboratory (NREL) estimated the annual performance degradation of monocrystalline and polycrystalline modules is 0.7% [5,6]. The LEEE-TISO (Laboratory of Energy, Ecology and Economy Solar-Ticino) test center of photovoltaic modules in Switzerland, stated that the degradation rate of the power of crystalline silicon PV modules could go from 0.7% to 9.8% during the first year of exposure and 0.7% to 4.9% during the second year of exposure [7]. Jordan states in the 2000s, degradation rate measured on individual modules and whole PV systems were 5% on average [8]. However, there is a piece of information on the degradation modes of PV modules in terms of frequency, rate of progression and degree of impact on the lifetime and reliability of the module. Research on photovoltaic modules is rather focused on the race to develop new technologies without sufficient return on those experiences that are already operational [9-11] .

Thus, it is important to develop a photovoltaic platform for measurements on real sites and relevant for long-term monitoring of PV module characteristics. This platform is installed in Senegal at Dakar to allow monitoring of degradation of different characteristics over time depending on the climatic conditions of the site. This paper presents the measurement platform and various elements that compose it. Weather and solar potential in Senegal are briefly presented. Finally, the methodology and initial results are exposed here-in-after.

Nomenclature

G	measured irradiance (W.m-2);
Tamb	ambient temperature (°C);
TNOCT	nominal operating cell temperature (°C);
Tref	standard reference temperature (°C);
A	current temperature coefficient (+ 22 µA/cm². °K);
β	voltage temperature coefficient (-2.2 mV /°K);
K	curvature coefficient (2 mW / ° K);
N	cells number of PV module;
Tmod	module temperature (°C);
Iscm	measured short-circuit current (A);
Vocm	measured open-circuit voltage (V);
Isc,stc	standardized short-circuit current (A);
Voc,stc	standardized open-circuit voltage (V);
Isci	initial short-circuit current in STC (A);
Voci	initial open-circuit voltage in STC (V);
ΔIsc	short-circuit current degradation (%);
ΔVoc	open-circuit voltage degradation (%);
S	PV cell surface (cm2);
Rs	series resistance of PV module (Ω).

2. Photovoltaic platform presentation

The photovoltaic platform shown in Fig. 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 [12]. Senegal has a significant solar potential with annual average radiation duration of about 3000 hours and an exposure rate of 5.7 kWh/m^2/d. This radiation varies between the northern part more sunlit (5.8 kWh/m^2/d in Dakar) and the southern part richest in terms of precipitation (4.3 kWh/m^2/d in Ziguinchor) [13]. 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 [12]. The relative humidity varies between 75% and 95% [14]. The platform is installed in Dakar between 17.28° West longitude and 14.43° North latitude to 31 meters altitude. The next section is devoted to the platform presentation and its different elements.

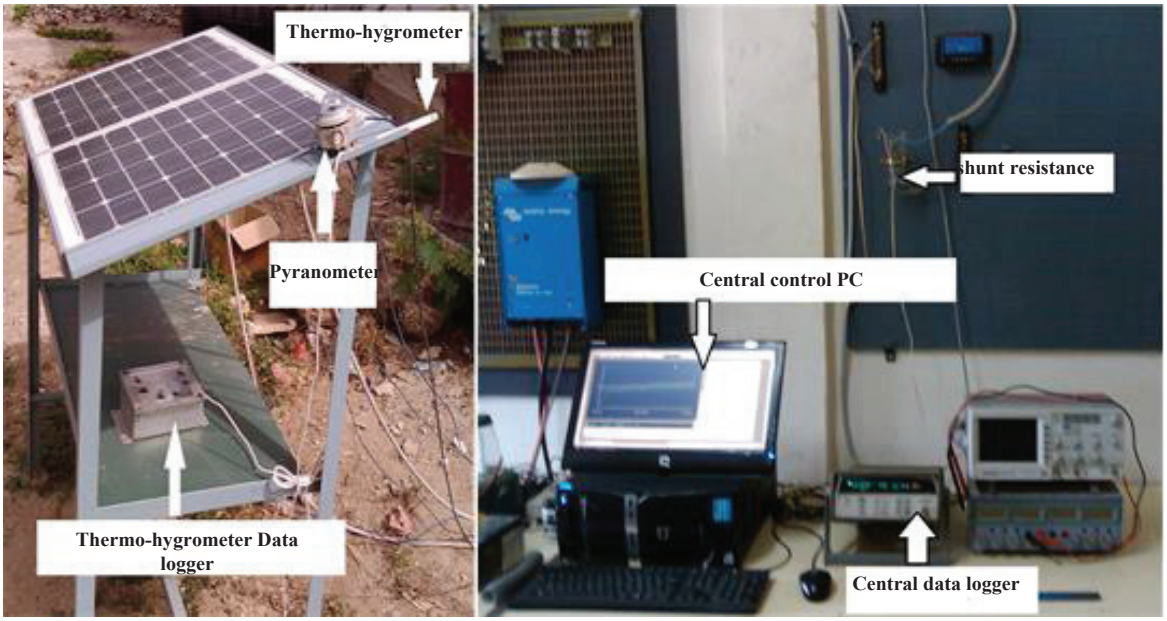

Fig. 1. Photovoltaic platform of measurements

Platform has been made operational since March 2012. It consists of two identical monocrystalline photovoltaic modules, four temperature sensors, thermo-hygrometer, pyranometer with data logger and PC.The technical characteristics of PV modules are given in Table1.

Table 1. Technical characteristics of PV modules

Specification	Values	Units
Nominal Peak power (P_c)	30	Watts
Short-circuit current (I_{Sc})	1.67	Amps
Open-circuit voltage (V_{oc})	21.50	Volts
Series resistance (R_s)	1.74	Ohms
PV cell surface (S)	49	cm^2
Cells number (N)	36	--
Fill Factor (FF)	0.72	--

2.1. Sensor of module temperature

These are thermocouples of types J placed on the inner surface of the module in order to measure the surface temperature. For each module, two thermocouples are bonded at diametrically opposed points. Averaging the two measurements on each module gives the surface temperature.

2.2. Sensor of ambient temperature and relative humidity

A Thermo-hygrometer of type KH-200 DN is used to measure ambient temperature and relative humidity. It includes a data acquisition system controlled by software KILOG [15]. Ambient temperature and relative humidity are measured simultaneously every minute.

2.3. Radiation Sensor

The radiation sensor used for measuring global radiation which reaches the PV module surface is a Kipp & Zonen CM11 pyranometer. It is placed at the same level as the PV modules [16].

2.4. Data acquisition

Measurements are carried out with a Agilent data logger. The platform is performed around a PC having the following features: Pentium Dual-Core 2.6 GHz 32-bit, 2 GB of RAM and 50 GB Hard Disk. The platform of measurements is piloted by the Agilent BenchLink Data Logger. The measurements of parameters (radiation, ambient temperature, module temperature, relative humidity, short-circuit current and open-circuit voltage) are performed every minute continuously.

3. Methods

The measurements performed by the platform must allow identifying and assessing degradation of electrical characteristics of PV modules such as I_{sc} and V_{oc} over time depending on the environmental parameters such as temperature and humidity. Electrical characteristics of modules on which we focus in this paper are short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}). Fig. 2 presents an overview of the methodology proposed in this work.

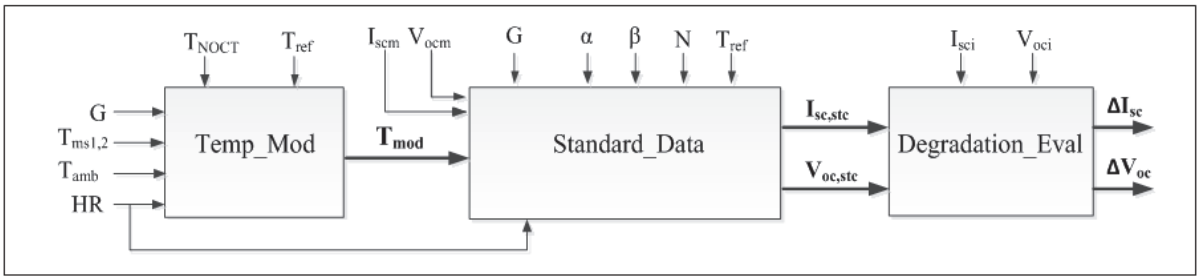

Fig. 2. Overview of methodology.

3.1. PV module temperature

The platform measures directly ambient temperature (T_{amb}) and surface temperature of PV module ($T_{ms1,2}$). Surface temperature of the module is also given by relation of Kenny (Equation 1) according to [17].

$$\boldsymbol{T_m = T_{amb} + \frac{G}{800}(T_{NOCT} - 20)} \quad (1)$$

Where, T_{NOCT} is the nominal operating cell temperature obtained with 800 W.m^{-2} radiation, 20°C ambient temperature, 1m.s^{-1} wind speed and 45° angle tilt of photovoltaic modules, according to IEC 61215 standard [18].

The value of T_{NOCT} for modules currently on the market varies from about 42 °C to 46 °C [19].

3.2. Measurements standardization

Measured Short-circuit I_{scm} and measured open-circuit voltage V_{ocm} in real operation are corrected to find their equivalents in standard test conditions (STC). From field measurements, it is possible to retrieve the standard value on standard test conditions (STC) characterized by a radiation of 1000 W.m^{-2} and temperature 25°C. Indeed, standard NF EN 60891: 1995-02 [20] in use for correction procedures depending on temperature and irradiance applying to measured current-voltage characteristics of silicon photovoltaic modules, gives general relations of correction equations (2) and (3).

$$I_s = I_m + I_{scm}\left(\frac{1000}{G} - 1\right) + \alpha S(T_{ref} - T_{mod}) \quad (2)$$

$$V_s = V_m - R_s(I_s - I_m) - KI_s(T_{ref} - T_{mod}) + \beta N(T_{ref} - T_{mod}) \quad (3)$$

Where, I_s represents the measured current which is standardized, I_m is the measured current in real conditions, I_{scm} is the measured short-circuit current, G is the measured irradiance, α is the current temperature coefficient, S is the PV cell surface, T_{ref} is a standard reference temperature and T_{mod} is a module temperature.
V_s is the measured voltage which is standardized and V_m is the measured voltage.
β is the voltage temperature coefficient, R_s is the series resistance of PV module, K is the curvature coefficient and N is the cells number of PV module.
In open circuit, curvature coefficient K which takes into account a loss of additional voltage near the elbow of the characteristic (current-voltage) is not considered [21]. Thus, the relationship corrective of measured short-circuit current and open-circuit voltage are given by equations (4) and (5). They are used in the block Standard_Data in Fig 2.

$$I_{sc,stc} = I_{scm}\left(\frac{1000}{G}\right) + \alpha S(T_{ref} - T_{mod}) \quad (4)$$

$$V_{oc,stc} = V_{ocm} + \beta N(T_{ref} - T_{mod}) \quad (5)$$

Equations (4) and (5) are used by Standard_Data standardization block (Fig. 2) to correct the measured short-circuit current and open-circuit voltage respectively I_{scm} and V_{ocm} to their equivalent in standard test conditions (STC) $I_{sc,stc}$ and $V_{oc,stc}$. These standard measurements are used for degradation evaluation of short-circuit current and open-circuit voltage.

3.3. Degradation evaluation of I_{sc} and V_{oc}

Degradation evaluation of short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of PV module is handled by Degradtion_Eval bloc in Fig 2. For each parameter, the measured value standardized is compared to the initial value given by the manufacturer before entry into service of photovoltaic module. The difference in percentage represents degradation of the parameter considered. Degradation of short-circuit current (ΔI_{sc}) and open-circuit voltage (ΔV_{oc}) is given respectively by equations (6) and (7).

$$\Delta I_{sc}(\%) = \frac{I_{sci} - I_{sc,stc}}{I_{sci}} X100 \quad (6)$$

$$\Delta V_{oc}(\%) = \frac{V_{oci} - V_{oc,stc}}{V_{oci}} X100 \quad (7)$$

Where, $I_{sc,stc}$ is the standardized short-circuit current , I_{sci} is the initial short-circuit current in standard test conditions (STC), $V_{oc,stc}$ is the standardized open-circuit voltage and V_{oci} is the initial open-circuit voltage in STC. The next section presents a few measurements made by the platform and the results from the proposed method.

4. Results and discussion

4.1. Environmental parameters

Three days are considered for the presentation of results. Indeed they are representative of the dry season season in Senegal [22].

Our main goal is to determine whether or not the electrical characteristic PV modules are degraded after one year of module operating. This was done by taking measurements on three typical days from photovoltaic platform. Sunlight exposure (G), ambient temperature (T_{amb}) and module temperature (T_{mod}) during these days are plotted in Fig 3. Ambient temperature (T_{amb}) can fall to around 18°C at night, but it reaches between 23.5 and 45°C during the day, depending on the amount of sunlight. Module temperature (T_{mod}) for three days evolves identically at ambient temperature but remains significantly above ambient temperature during the day. However, the module temperature is below the ambient temperature during the night.

Module temperature is an important parameter for monitoring the behavior of the PV module over time. In Fig. 4 are shown the measured module temperature on the three days and the simulated module temperature from Kenny relationship (1).

We compared our simulation results with the measured data. There is good agreement for the data measured on the three days. The simulated and measured module temperatures were compared quantitatively via a linear correlation coefficient R^2 given by equation (8).

$$R^2 = 1 - \frac{\sum(X_i - \bar{X}_i)^2}{\sum(X_i - \bar{X}_i)^2} \quad (8)$$

Where X_i is the measured data, $\tilde{X}_i$ is the simulated data and $\bar{X}_i$ is the arithmetic mean of the measured data. The higher the value of R^2 the stronger the linear correlation between the simulated and the measured module temperature, i.e. the better the simulation performance.

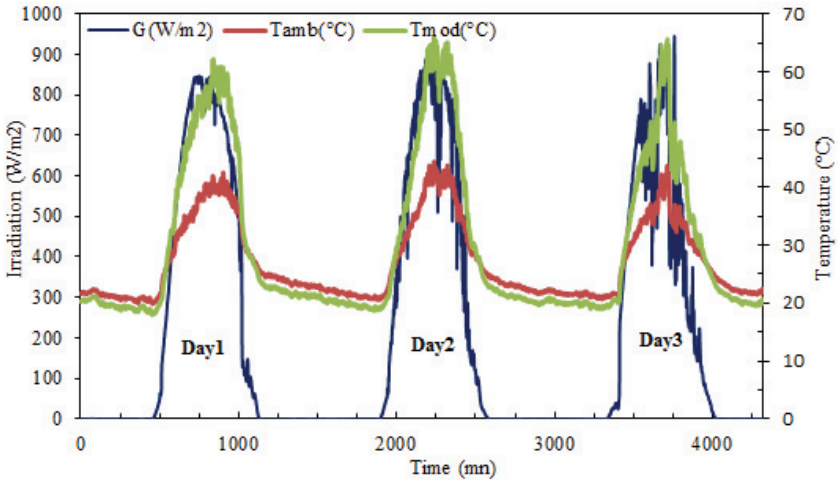

Fig. 3. Time course of Irradiation, ambient temperature and module temperature on three different days.

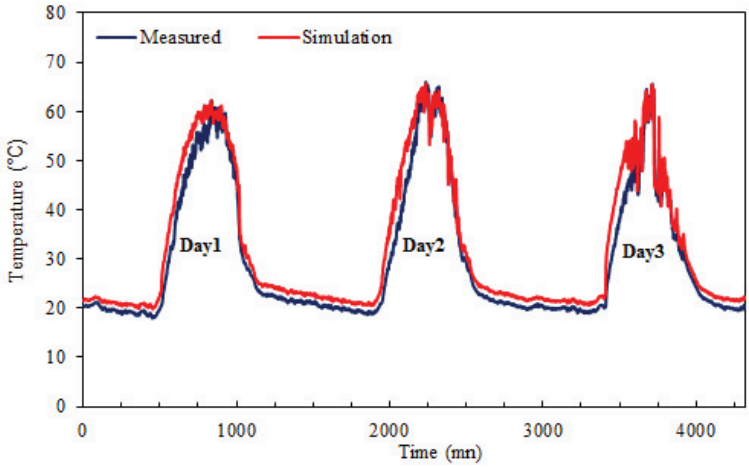

Fig. 4. Comparison of measured module temperature (blue) and simulated module temperature (red).

The correlation coefficients for the five days are 0.95, 0.93, 0.97, 0.96 and 0.98, respectively (Fig. 5). The large values of R^2 for all days confirm the overall accuracy of the Kenny relationship (1).

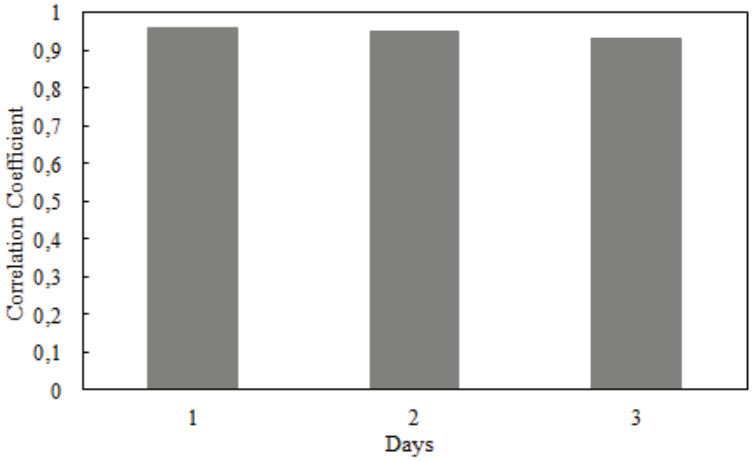

Fig. 5. Correlation Coefficients

4.2. Standardization of measurements

Measurements obtained from platform are done under real conditions which are very dependent on environmental conditions. Environmental parameters are highly variable depending on season and time as illustrated in Fig. s 3 and 4. For making comparative studies of measures, they must be performed in the same conditions. The proposed method consists in bringing the real measurements in the standard test conditions (STC) thanks to the proposed method and implemented in Standard_Data bloc in Fig 2. Direct and Standardized measurements of short-circuit current and open-circuit voltage measured on the three days considered in this study are presented. Fig. 6 shows the direct measurements of short-circuit current (I_{scm}) and open-circuit voltage (V_{ocm}) for the three days. We note that when the PV module begins to produce, the open-circuit voltage increases rapidly to reach its nominal value and keeps it throughout the day. The Short-circuit current evolves such as irradiation and reaches its maximum when the irradiation is maximum.

In Fig. 7 and Fig. Fig. 8 are shown respectively standardized short-circuit current ($I_{sc,stc}$) and standardized open-circuit voltage ($V_{oc,stc}$) for the three days.

Fig. 7 clearly shows that the standardized short-circuit current remains relatively constant during the day despite the variation in radiation and short-circuit.current. In Fig. 7, only the values corresponding to the central hours of the day should be considered.

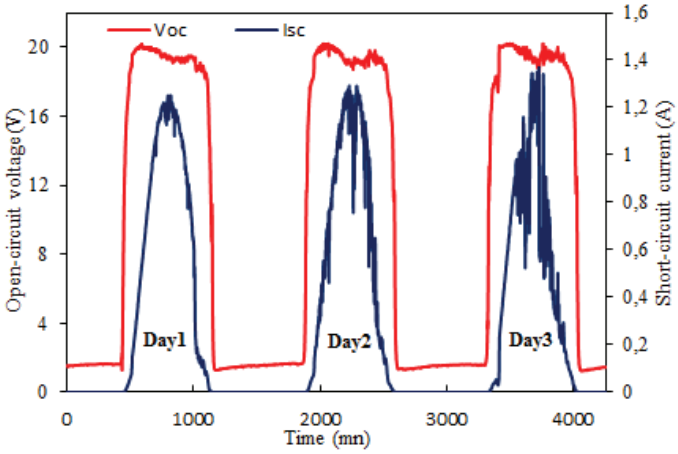

Fig. 6. Time course of measured Open-circuit voltage (red) and measured Short-circuit current (blue) on the three different days.

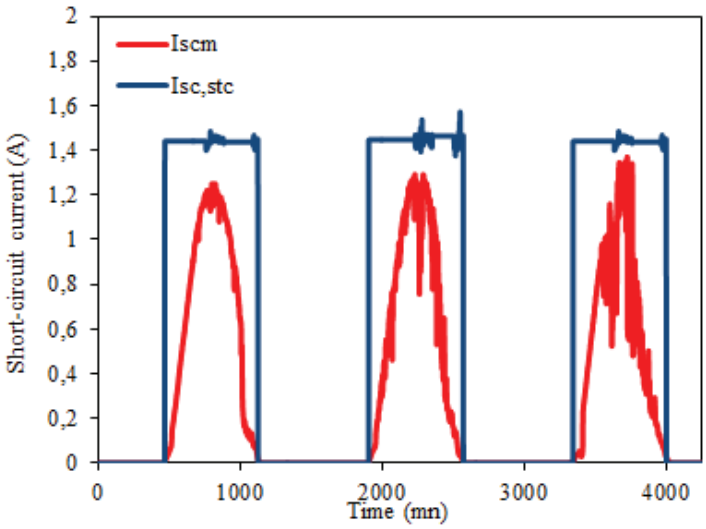

Fig. 7. Comparison between measured short-circuit current (I_{scm}) and standardized short-circuit current ($I_{sc,stc}$) on the three different days.

The standardized open-circuit voltage remains almost relatively constant during the daylight despite the variation according to radiation on the three days studied as shown in Fig. 8. Indeed, the voltage is less dependent on radiation in comparison to short circuit current.

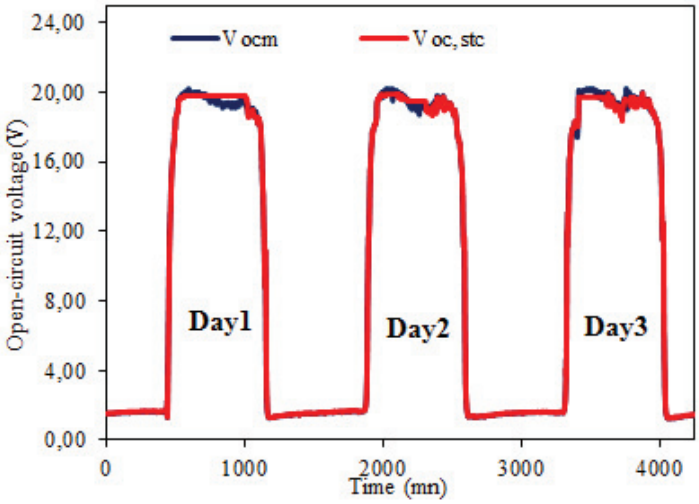

Fig. 8. Comparison between measured Open-circuit voltage (V_{ocm}) and standardized Open-circuit voltage ($V_{oc,stc}$) on the three different days.

The Fig. 9. present the correlation between the measured open-circuit voltage (V_{ocm}) and standardized open-circuitvoltage ($V_{oc,stc}$). It shows that these two parameters are well correlated for the regarded three days and therefore our standardization method is reliable.

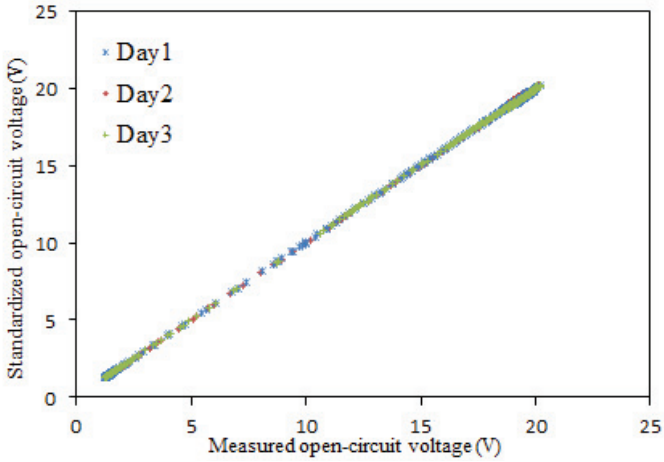

Fig. 9. Correlation between the measured open-circuit voltage (V_{ocm}) and standardized open-circuit voltage ($V_{oc,stc}$).

4.3. Degradation evaluation

Fig. 10 presents degradation of the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the PV module after ten months of operation at the Dakar University site. These results are derived from the platform measurements and investigation method proposed in this paper. In Fig. 10, only values in the central framed area must be considered because it matches the production hours of PV modules. Degradation of short-circuit current is about 13,5% for the three days. The data ranges outside of sunny days are not interesting because during this period the module does not produce. However, it remains difficult to identify the causes of degradation that can many and diverse [23].

Realini gives 6% to 13% degradation of short-circuit current below the nominal value when PV module is attained by discoloration phenomenon [24].

The degradation of open-circuit voltage measured during the three days is about 8%. In [24], it is argued that almost

no degradation of open-circuit voltage of PV module crystalline silicon occurs after ten operation years.
The results presented on the degradation of short-circuit current and open circuit voltage give an overview of the proposed method. This paper is focused on the presentation of the method used and the platform developed.

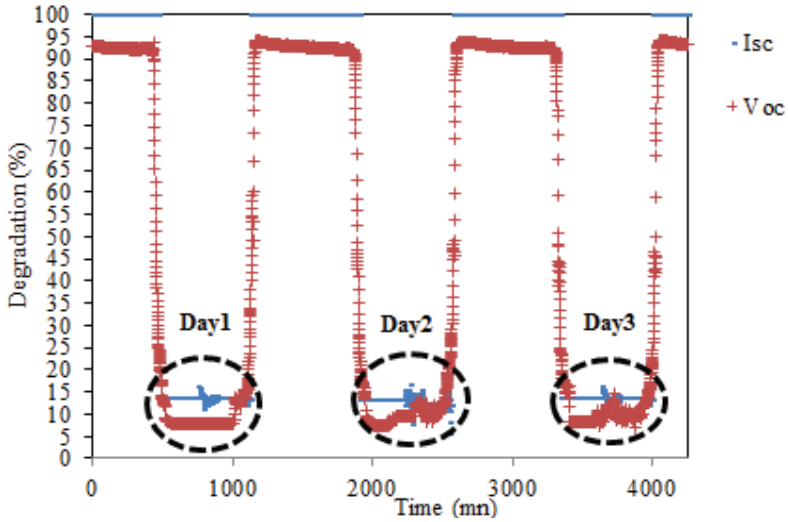

Fig. 10. Degradation of short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of PV module after ten months of operation.

5. Conclusion

Toward this survey, the platform installed in Senegal and dedicated to studies on the degradation of the electrical characteristics of photovoltaic modules has been presented. Measurements of environmental parameters of three typical days were discussed. Standardization methods for direct measurement of short-circuit current and open-circuit voltage is also proposed. Finally, assessment strategy for degradation of short-circuit current and open-circuit voltage is presented. However, it is still difficult to assess quantitatively these first results on PV modules degradation. Indeed, it is still rare to find research work that clearly gives values on degradation of the electrical characteristics of PV modules. On the other hand, our study focuses on a short measurement period of ten months. In perspective, kind study may require a long period of operation of the platform in order to obtain a database more meaningful. It will quantify this degradation of electrical characteristics of PV modules over a longer period and in different seasons. Also it will be very interesting to work on PV modules of different technologies.

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