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Comparison of the Methods of Calculation of Measurements Standardization on the Outdoor Photovoltaic Modules

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Abstract: To compare the performance of PV modules, it was required to translate the measured I - V characteristics, to use certain standard conditions. The International Electrotechnical Committee (IEC) has defined the standard test condition (STC) for PV modules with 1000 W/m^2 irradiance with AM 1.5 and 25°C module temperature. The IEC has also published some standard correction procedures (contained in IEC 60891) to translate irradiance and temperature values between different. IEC 60891 defines a procedure which helps to translate the measured I-V characteristics photovoltaic devices at standard test condition (STC). The IEC 60891 translation procedures can be applied only for the 20% variation in the irradiance, the irradiance should not be below 800 W/m^2 for translation at STC but also for limit temperatures (35 ° VS). In our study we will use crystal technology and the temperature measurements carried out at the study site show temperatures varying from 55°C to 65°C. Data from tests in the wild has been converted to standard test conditions (STC) using four methods proposed by AJ Anderson and G. Blaesser, the combination method and the equations from international standard IEC 60891. These methods are compared using data from one year and the correlation between the measured data and the standardized data. The results demonstrated that the combination method has good precision in the STC conversion of the performance of the PV module under different climatic and technological conditions. Then, based on the investigation results of the conversion equations, these translation methods are distinguished by the type of solar cell technology and the field of application. There is a difference between in situ and natural tests, attributed to various factors but mainly to the mismatch between the spectral responses of the PV module and the reference solar cell. The combination method uses irradiance data and temperature and performance parameters under STC conditions of PV modules to predict the maximum output power. Therefore, it is essential to provide reliable weather data before designing photovoltaic power systems.

Keywords: Photovoltaic Module, Performances, Translation, Standard Conditions

1. Introduction

Recent studies have shown that 83% of solar photovoltaic (PV) modules are made from crystalline silicon solar cells [1]. However, the photovoltaic modules are installed in a real environment where the operating conditions are very different from STC conditions. In addition, photovoltaic technologies behave differently with changing weather conditions. Several authors have suggested models to predict performance of photovoltaic modules in real operating conditions [2, 3, 4]. During the survey, module I-V data were measured at different conditions of irradiance and temperature. In order to compare their performance, it was required to translate the measured I-V data to some standard condition. International Electrotechnical Committee (IEC) has defined standard test condition (STC) for PV modules as 1000 W/m^2 irradiance with AM 1.5G spectrum and 25°C module temperature. IEC has also published some standard correction procedures (contained in IEC 60891) for translating between different irradiance and temperature values [5]. We have used a modified version of IEC 60891 correction procedure 1 [6, 7, 8, 9] for translating our survey data. Also, the stability of peak power of crystalline silicon PV module before and after long term outdoor exposure is a crucial parameter for the reliability and durability. However, when evaluating PV performances in environmental operating conditions (EOC), for a practical use, it is difficult to create the measurement conditions identical to STC (Irradiation intensity 1000 W/m^2, module temperature 25°C, Air Mass 1.5). Therefore, in most cases the PV module output characteristic values measured with I-V curve tracer are converted into STC values based on various methods [10]. This paper summarizes the electrical characterizations of crystalline silicon PV modules in outdoor exposure of natural sunlight of Dakar site (Senegal). All results are reported to STC conditions by using four methods for comparative study with manufacturer data sheet.

2. Literature Review

2.1. Models of Electrical Parameters of a PV Module: Dependence on Meteorological Parameters

It is well known that temperature plays a central role in the operation of photovoltaic systems [11]. The behavior of a photovoltaic module is not only governed by the level of irradiance (flow of incident photons) which reaches its surface, but also by the temperature of the cells which in turn is affected by other factor such as wind speed, rain and module mounting type. It affects the module electrical parameters such as the open circuit voltage and the short-circuit current.

2.1.1. Short Circuit Current and Open Circuit Voltage Dependence on Irradiance

The most important parameter in the solar conversion process is the irradiance. On the one hand, the short-circuit current is directly linked to the irradiance [12]. This relationship is generally given by Equation (1).

$$I_{sc}(G) = I_{sc(STC)} * \left(\frac{G}{G_{STC}}\right) \quad (1)$$

With, G_{STC} and $I_{sc(STC)}$ are irradiance and short-circuit current in the STC conditions respectively. On the other hand, the voltage varies logarithmically with irradiance

$$V_{oc}(G) = \frac{V_{oc(STC)}}{\left[1+\delta\, ln\left(\frac{G_{STC}}{G}\right)\right]} \quad (2)$$

With, $V_{oc(STC)}$ is open circuit voltage in STC conditions and δ is a dimensionless coefficient because of the logarithmic nature of equation (2). For monocrystalline technology modules, δ is equal to 0,085 [13].

2.1.2. Short Circuit Current and Open Circuit Voltage Dependence on Temperature

Temperature directly affects the electrical power of the photovoltaic module and consequently the efficiency of the photovoltaic system. Temperature affects the electrical parameters of the PV module. Consequently, the operating PV module temperature is an important parameter in the assessment and prediction of PV systems performance. The increase in temperature is due to the increase in irradiance. Facing this temperature increase, the short-circuit current increases slightly while the open circuit voltage decreases. For the silicon photovoltaic module, the short-circuit current and the open circuit voltage dependence on the temperature [14] is given by Equations (3) and (4).

$$I_{sc}(Tc) = I_{sc(STC)} + \alpha * (T_c - T_a) \quad (3)$$

$$V_{oc}(Tc) = V_{oc(STC)} + \beta * (T_c - T_a) \quad (4)$$

With α=(dI_{SC}/dT_C), β=(dV_{OC}/dT_C) are the temperature coefficients of current and voltage of the PV module, respectively. In Equations (3) and (4), the temperature coefficients are expressed in (A/°C) and (V/°C) respectively.

2.1.3. Model of Short-Circuit and Open Circuit Voltage as a Function of Irradiance and Temperature

During the day, PV modules operate in conditions of varying irradiance and temperature. These conditions are often different from STC conditions in which the PV modules are rated by manufacturer. It is therefore necessary to assess the performance in function of meteorological parameters variation. The variation of short-circuit current and open circuit voltage as a function of irradiance and temperature is given by Equations (5) and (6).

$$I_{sc}(G, Tc) = I_{sc(STC)} * \left(\frac{G}{G_{STC}}\right) * \left(1 + \alpha(T_C - T_a)\right) \quad (5)$$

$$V_{oc}(G, Tc) = \frac{V_{oc(STC)}}{\left[1+\delta \ln\left(\frac{G_{STC}}{G}\right)\right]} * (1 + \beta * (T_C - T_a)) \quad (6)$$

Temperature coefficients in Equations (5) and (6) are expressed in (°C^{-1}).

2.2. Module Temperature Assessment

The temperature of the PV module can be calculated by using several correlations given by the literature [11]. The correlations proposed in literature express the operating temperature depending on meteorological variables (ambient temperature, wind speed, solar irradiance, etc.) and the properties of the photovoltaic module (transmittance and absorbance etc.). Nominal operating conditions temperature (NOCT) model [15], it depends on the ambient temperature and global solar irradiance. In this case, the module is rack-mounted, and the module temperature can be assessed using linear approximation equation (7)

$$T_C = T_a + \left(\frac{T_{NOCT}-20}{G_{NOCT}}\right) * G \quad (7)$$

With, Ta, the ambient temperature; G, the global solar irradiance; TNOCT and GNOCT are module temperature and irradiance under nominal operating conditions (NOC) (wind speed = 1 m/s, G = 800 W/m² and Ta = 20°C) respectively.

2.3. The STC Conversion Equations

The Table shows STC conversion equations, J. Anderson [16], G. Blaesser [17] and as well as the equations already standardized as IEC 60891 [18].

Table 1. *Short circuit current with different method.*

Short circuit current	
IEC 60981	$I_{sc,2} = I_{sc,1} + I_{sc,EOC} * \left(\frac{G_2}{G_1} - 1\right) + \alpha * (T_2 - T_1)$
Anderson's method	$I_{sc,2} = \frac{I_{sc,1}}{[1 + \alpha * (T_1 - T_2)] * \left(\frac{G_2}{G_1}\right)}$
Blaesser's method	$I_{sc,2} = I_{sc,1} * \left(\frac{G_2}{G_1}\right) * (1 + \alpha * (T_2 - T_1)$

Table 2. *Open circuit voltage with different method.*

Open circuit voltage	
IEC 60981	NO equation available for the direct comparison
Anderson's method	$V_{oc,2} = \frac{V_{oc,1}}{[1+\beta*(T_1-T_2)]*\left[1+\mu \ln\left(\frac{G_2}{G_1}\right)\right]}$
Blaesser's method	$V_{oc,2} = V_{oc,1} * (1 + D_V)$ $D_V = \delta \ln\left(\frac{G_2}{G_1}\right) + \beta * (T_2 - T_1)$

Table 3. *Maximum power with different method.*

Pmax, Maximum power	
IEC 60981	NO equation available for the direct comparison
Anderson's method	$P_{max,2} = P_{max,1} * \frac{G_2}{G_1} * \frac{V_{oc,1}}{[1 + \gamma * (T_1 - T_2)] * \left[1 + \mu \ln\left(\frac{G_2}{G_1}\right)\right]}$
Blaesser's method	$P_{max,2} = FF_2 * V_{oc,2} * I_{sc,2}$ $FF_2 = FF_1 * \left(\frac{(V_{mp,2}}{V_{mp,1}}\right)$

Table 4. *The I-V curve current with different method.*

I – V curve	
IEC 60981	$V_2 = V_1 - (\beta * (T_2 - T_1)) - R_S * (I_1 - I_2) - k * (T_2 - T_1)$ $I_2 = I_1 + I_{sc,1} * \left(\frac{G_2}{G_1} - 1\right) + \alpha * (T_2 - T_1)$
Anderson's method	$V_2 = V_1 * \left(\frac{V_{oc,2}}{V_{oc,1}}\right)$ $I_2 = I_1 * \left(\frac{I_{sc,2}}{I_{sc,1}}\right)$
Blaesser's method	$V_2 = V_1 + DV + R_s * (I_1 - I_2)n$ $DV = V_{oc,2} - V_{oc,1}$ $I_2 = I_1 * \left(\frac{I_{sc,2}}{I_{sc,1}}\right)$

Table 5. *Range of application with different method.*

Range of application	
IEC 60981	Crystalline; Irradiance: 700 W/m²; Module temperature: 15-35°C
Anderson's method	Crystalline-Amorphous Irradiance: 100-1000 W/m²; Module temperature: 25-75°C
Blaesser's method	Crystalline; Irradiance ≥600 W/m²;

Table 6. Specifications (STC) of the Photovoltaic module using.

Parameters	Value
Nominal Peak power (Watts)	30
Short-circuit current (Amperes)	2
Open-circuit voltage (Volts)	22.50
Fill Factor (-)	0.72
PV cell surface (cm^2)	49
Cells number (-)	36
Current temperature coefficient (%)	+0.037/°C
Voltage temperature coefficient (%)	-0.34/°C

Where the nomenclature is described as:
E: irradiance; T: Temperature;
FF: Fill factor; Rs: Module serial resistance;
K: Curve compensation factor;
α: Reduced temperature coefficient of Isc;
β: Reduced temperature coefficient of Voc;
γ: Reduced temperature coefficient of Pmax;
μ: Irradiance dependency Coefficient [19].
Only the irradiance dependency coefficient (μ) is deduced from the literature reference [20].

3. Materials and Methods

3.1. Materials

The data are measured for 30Wp monocrystalline module installed at Dakar. The characteristics of PV module are given in Table 6.

3.2. Methods

In this work the instantaneous values (increments of one minute) of the electrical parameters have been used including the short-circuit current and the open circuit voltage in order to quantify the meteorological parameters effect on the real performance of photovoltaic modules. We have named this procedure as correction Combination's method.

$$I_{sc} = \frac{I_1}{[1+\alpha*(T_1-T_2)]*\left(\frac{G_2}{G_1}\right)} \quad (8)$$

$$V_{oc} = V_1 + \left(\beta * (T_2 - T_1)\right) \quad (9)$$

To assess the maximum power output of PV module, we have used equation (10) that defines the fill factor (FF) and links short circuit current and open circuit voltage with the maximum power output [21].

$$FF = \frac{P_{max}}{I_{sc}*V_{oc}} \quad (10)$$

Fill factor is the measure of the quality of the p-n junction and the series resistor of the PV cell. It is a function of the open circuit voltage and the cell operating temperature [22]. The empirical expression for this relationship is given by equation (11).

$$FF = \frac{v_{oc}-ln(v_{oc}+0.72)}{v_{oc}+1} \quad (11)$$

Where , v_{oc} is defined as the open circuit voltage normalized to the thermal voltage. It is given by $v_{oc} = \frac{V_{oc}}{v_T}$ with, $v_T = \frac{k_B T_C}{q}$ is the thermal voltage. From equations (8, 9, and 11), the maximum power output can be assessed by equations (12, 13)

$$P_{max} = I_{sc} * V_{oc} * FF \quad (12)$$

$$P_{max} = \left(\frac{I_1}{[1+\alpha*(T_1-T_2)]*\left(\frac{G_2}{G_1}\right)}\right) * \left(V_1 + \left(\beta * (T_2 - T_1)\right)\right) * \frac{V_{oc}-ln(v_{oc}+0.72)}{v_{oc}+1} \quad (13)$$

4. Results and Discussion

Data acquired EOC on a clear sunny day was converted into solar output characteristics in STC by using four conversion methods suggested by J. Anderson [16], G. Blaesser [17], Combination's method and as well as the equations already standardized as IEC 60891 [18]. We have studied four methods of PV modules using the irradiance and ambient temperature data (G; Ta) and the intrinsic performance parameters of the PV module in STC conditions (Isc; Voc; FF; α; β; γ, δ) examining the performance of the models is performed by comparing the measured values of the maximum power output and those calculated by the different models studied (Figures 1, 2, 3, 4). The meteorological (G; Ta) and electrical (Isc; Voc) parameters data have been measured and collected increments of one minute. The data are measured for 30Wp monocrystalline module installed at Dakar. The characteristics of PV module are given in Table (6). The comparison of measured data and standardize values by the different methods for one year is performed Figure 5 (a) and Figure 6 (a). The correlation between these data is presented for data from one day of the year Figure 5(b) and Figure 6(b). The results of the comparison by the different methods are presented as follows.

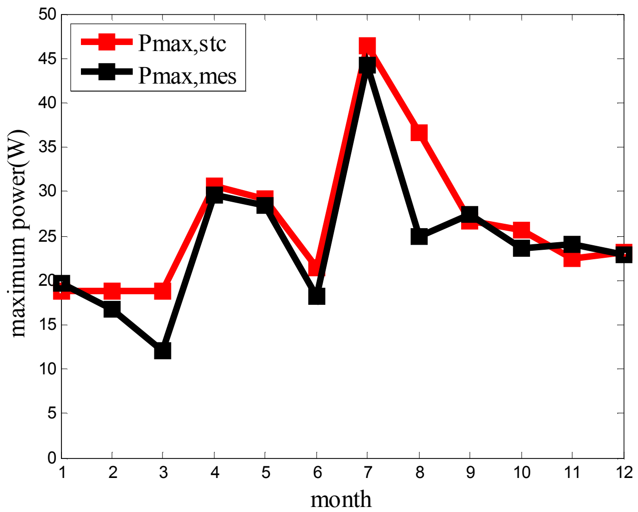

Figure 1. *Curve of maximal power measured (black) and translate (red) obtained with the Combination's method.*

In our case the values of the moderate temperatures of modules are > 25°C and go as far as reaching (affecting) 65°C and the values of the obtained period of sunshine turn (shoot) around 900 in 1200 W/m². Consequently, the method IEC 60981 is not applicable any more for measures on real sites for Isc and Voc. This is owed to the fact that the conversion to the been worth STC with method has IEC 60891 has limitation in the tidy up of application (crystalline solar cell material, irradiance > 700 W/m^2 and modulate temperature 35°C).

The examination of the curves of power moderate and standardized with four methods show good that with the Combination's method, we have a good correlation and an error between both curves is very low. The Combination's method verifies the on-site conditions reality for the current of short circuit, open circuit voltage and the maximal power. What will allow us to work with this method which is more adapted for our measure.

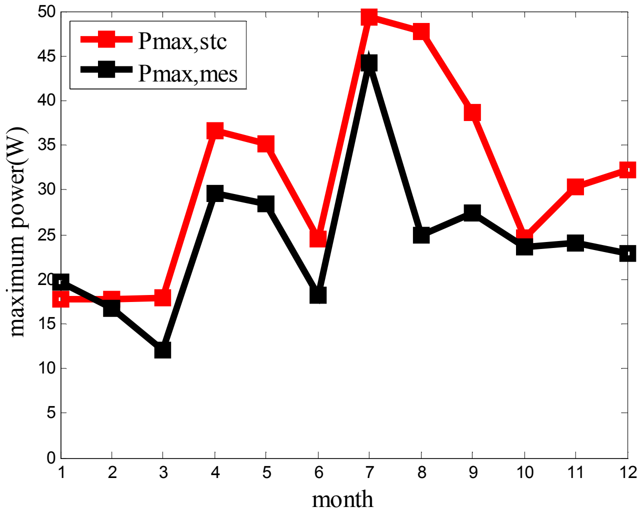

Figure 2. *Curve of maximal power measured (black) and translate (red) obtained with the method of Anderson.*

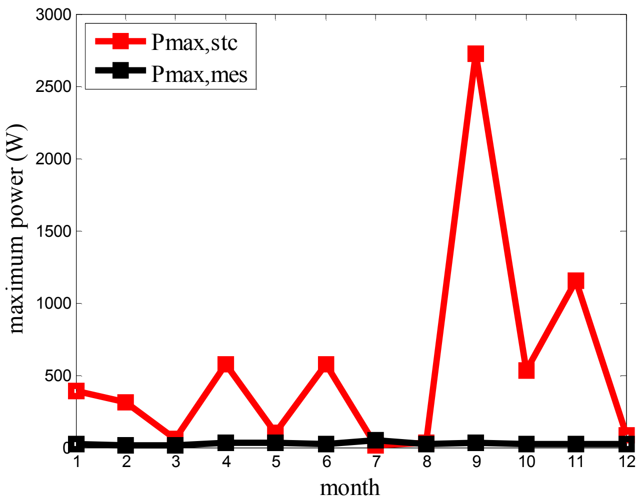

Figure 3. *Curve of maximal power measured (black) and translate (red) obtained with the method of IEC 60981.*

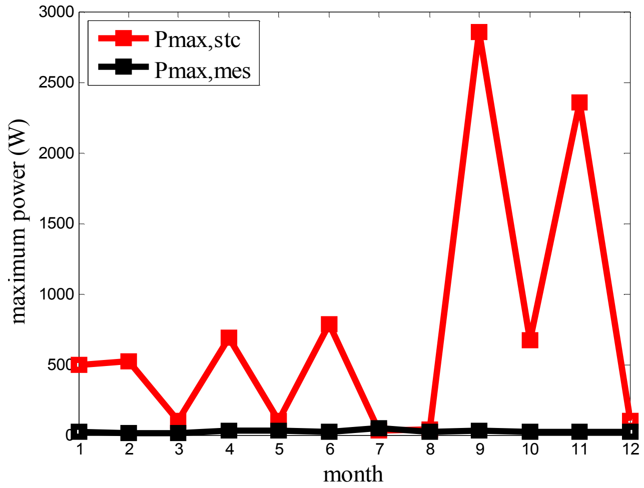

Figure 4. *Curve of maximal power measured (black (red) and translate (red) obtained with Bleasser's method.*

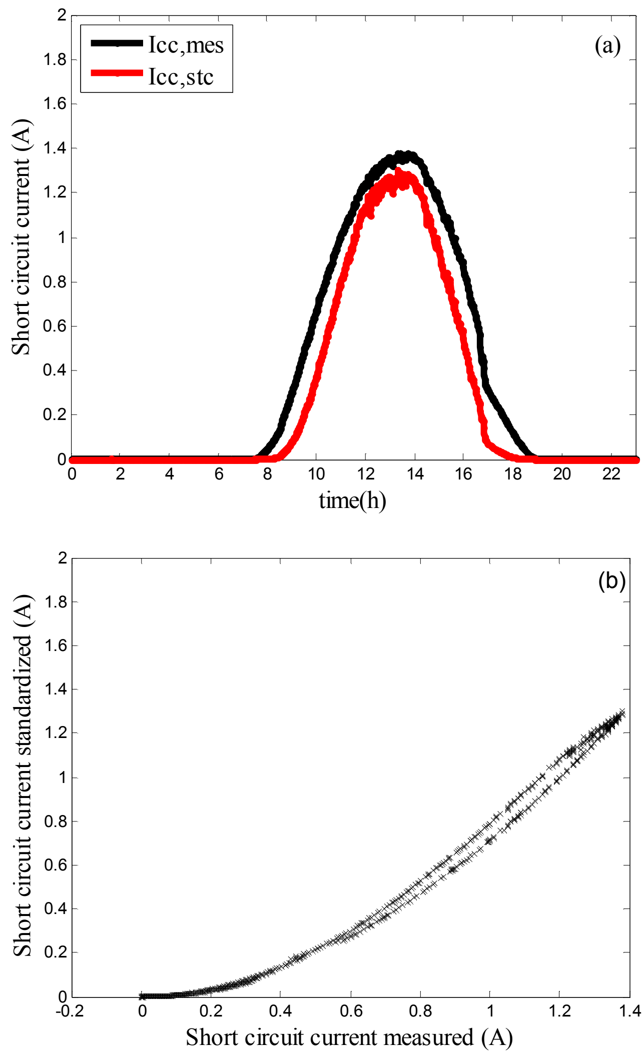

Figure 5. *Comparaison (a) and correlation (b) between measured and standardized short-circuit current (Isc) with Combination's method.*

Direct and Standardized measurements of short circuit current and open-circuit voltage measured on one days in the year considered in this study are presented. Figure 5 (a) and

Figure 6 (a) shows the direct measurements of short-circuit current (Icc, mes) and open-circuit voltage (Voc, mes) and standardized short-circuit current (Isc, stc) and standardized open circuit voltage (Voc, stc) for one day.

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. Figure 5(a) clearly shows that the standardized short-circuit current varied with the short-circuit current measured during the day despite the variation in radiation and short circuit current. In Figure 5 (a) only the values corresponding to the central hours of the day should be considered.

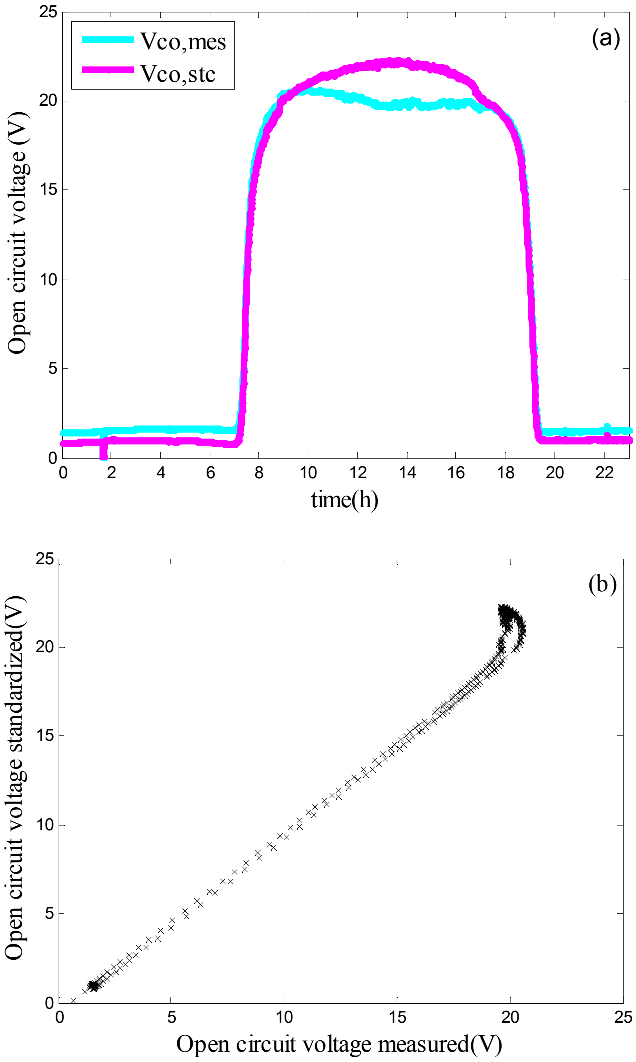

Figure 6. *Comparaison (a) and correlation (b) between measured and standardized Open-circuit voltage (Voc) with Combination's method.*

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 Figure 6 (a). Indeed, the voltage is less dependent on radiation in comparison to short circuit current. For every parameter; the correlation enters the standardized and moderate value is estimated and presented Figure 5 (b) and Figure 6 (b) shows that the current of moderate short circuit varies and evolves in the same sense as the current of standardized short circuit as well as the moderate and standardized tension.

5. Conclusion

In this study, four methods of STC conversion of silicon PV modules are presented and analyzed. The performance of the method was tested on a monocrystalline PV module 30 Wp. The PV module has been exposed in a real environment. Data of irradiance and temperature as well as the short circuit current and open circuit voltage of the module are used in the experimental validation of the method.

IEC 60981, Anderson's method, Blaesser's method and Combination's method are compared using data of one day and one year and the correlation between the data measured and those calculated using each method are analyzed. The results demonstrated that Combination's method has a good accuracy in the STC conversion of the PV module performance in different weather conditions. The Combination's method uses data from the irradiance and temperature and performances parameters in STC conditions of module PV to predict the maximum power output. Therefore, it is essential to be provided with reliable meteorological data before designing PV power systems.

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