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Degradation and Performance Evaluation of PV Module in Desert Climate Conditions with Estimate Uncertainty in Measuring

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Abstract: The performance of photovoltaic (PV) module is affected by outdoor conditions. Outdoor testing consists installing a module, and collecting electrical performance data and climatic data over a certain period of time. It can also include the study of long-term performance under real work conditions. Tests are operated in URAER located in desert region of Ghardaïa (Algeria) characterized by high irradiation and temperature levels. The degradation of PV module with temperature and time exposure to sunlight contributes significantly to the final output from the module, as the output reduces each year. This paper presents a comparative study of different methods to evaluate the degradation of PV module after a long term exposure of more than 12 years in desert region and calculates uncertainties in measuring. Firstly, this evaluation uses three methods: Visual inspection, data given by Solmetric PVA-600 Analyzer translated at Standard Test Condition (STC) and based on the investigation results of the translation equations as ICE 60891. Secondly, the degradation rates calculated for all methods. Finally, a comparison between a degradation rates given by Solmetric PVA-600 analyzer, calculated by simulation model and calculated by two methods (ICE 60891 procedures 1, 2). We achieved a detailed uncertainty study in order to improve the procedure and measurement instrument.

Keywords: Photovoltaic Module, Translation, Solmetric PVA-600 Analyzer, Visual inspection, Degradation Rate, Uncertainty Analysis.

1 Introduction

The photovoltaic system (PV) has attracted much attention due to the oil and environment pollution in recent years [1 – 3]. Its merits are: inexhaustible; pollution-free; abundant; silent and with no rotating parts and size-independent electricity conversion efficiently. The main drawback is that: Form an operational point of the view, a photovoltaic array experiences large variation of

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its output power under intermittent weather conditions. These phenomena may cause operational problems at a central control center in a power utility, such as excessive frequency deviations, spinning reserve increase...etc. Its initial installation cost is considerably high. Integrating the PV power plant with other power sources such as diesel backup [2], fuel cell backup [3], battery backup [1, 3] super conductive magnetic energy storage backup are ways to overcome variations of its output power problem. The performance of solar modules varies according to the environmental conditions and gradually deteriorates during the years [4 – 9]. An important factor in the performance of PV module has always been their long-term reliability. The most important issue in long-term performance assessments is degradation which is the result of a power or performance loss progression dependent on a number of factors such as solar irradiation and ambient temperature, humidity, wind, water ingress and ultraviolet (UV) intensity [10 – 13]. Degradation of PV modules is essentially a combination of two phenomena [14]:

- An initial, very rapid decrease in efficiency within the first few days of exposure,
- A long-term reduction in efficiency over the year.

In [15] the initial power loss for crystalline silicon PV modules is estimated between 2.3% – 3.9% and in [16] between 2% – 3%. Also Rabii et al. [17] report a 60% average loss over 12 years. For example, a study by Tang et al. [18] of modules exposed for 27 years in desert region found that those modules who survived experienced an average degradation of 1.1% per year. Jordan et al [19] calculated a rate of 1.24%/year considering various technologies and climates. Recently, the measurements carried out provided a mean power degradation rate of 1.17%/year for mono-crystalline silicon PV modules tested under real work conditions [20].

In the present paper, a comparative analysis of different methods to evaluate the degradation rates of PV module in desert environment of Ghardaïa (Algeria). Measurements in this work are taken with an I-V curve tracer (Solmetric PVA-600 PV Analyzer). The Solmetric tool is a commercially available curve tracer that is used by installers [21]. To compensate the temperature effects and convert the values to STC two methods were assessed (procedure 1.2). The uncertainty in measurement is fundamentally important for solar energy. Without an uncertainty declaration, the quality of a result cannot be quantified. Measurement results are incomplete and meaningless without a declaration of the estimated uncertainty with traceability to the International System of Units (SI) or to another internationally recognized standard [22]. The corresponding uncertainty of each method was calculated based on the Guide to the Expression of Uncertainty in Measurement [23] and present the results of our uncertainty analysis.

This paper consists of six sections, including the introduction. Section 2 introduces the model and simulation procedure, and Section 3 illustrates the experimental results. Section 4 describes the evaluation and analysis of degradation and Section 5 contains the standard uncertainties and uncertainty analysis. Finally, the conclusions of the study are given in Section 6.

2 Model and Simulation Procedure

In order to evaluate the degradation rate of PV modules, it's necessary to have information about their initial characteristics. In this study, we have chosen the modeling of PV modules and the extraction of the module parameters are obtained using an accurate method proposed by [24, 25].

2.1 Model of Practical PV

Photovoltaic (PV) arrays are built up with combined series/parallel combinations of PV solar cells [26], which are usually represented by a simplified equivalent circuit model such as the one given in Fig. 1 and/or by (1). In obscurity, the solar cell is not an active device; it works as a diode, i.e. a p-n junction. It produces neither a current nor a voltage. However, if it is connected to an external supply it generates a current I_d, called diode (D) current or dark current. The one diode determines the I-V characteristics of the cell [25].

$$I = I_{ph} - I_0\left(e^{\left(\frac{V+IR_s}{V_t}\right)} - 1\right) - \frac{V+IR_s}{R_{sh}}, \tag{1}$$

where

$$I_{ph} = \frac{G}{G_{STC}} I_{ph,STC}\left[1 + \alpha\left(T_c - T_{c,STC}\right)\right],$$

$$I_0 = I_{rs}\left(\frac{T_c}{T_{c,STC}}\right)^3 \mathrm{e}^{\left[\frac{qE_g\left[\frac{1}{T_c}-\frac{1}{T_{c,STC}}\right]}{Ka}\right]},$$

$$R_{sh} = R_{ph,STC}\frac{G}{G_{STC}}, \qquad R_s = R_{s,STC}.$$

V_t is the thermal voltage, $V_t = a\mathrm{K}T_c/q$, K is the Boltzmann constant (1.38×10^{-23} J/K), q is the electron charge (1.602×10^{-19} °C). I is the cell output current (A), I_{ph} is the photocurrent, function of the irradiation level and junction temperature, I_0 is the reverse saturation current of diode. R_s and R_{sh} are the series and shunt resistance respectively, $T_{c,STC}$ is the reference cell operating temperature (25°C), V is the cell output voltage, α is the current temperature coefficient, I_{STC} is the short circuit current at Standard Test Condition (STC), while G_{STC} and T_{STC} are the irradiation and temperature of the PV module at STC, respectively, I_{rs} is the cell reserve saturation current at a reference temperature and a solar irradiance, E_g is the band-gap energy of the material, a is the ideal factor .

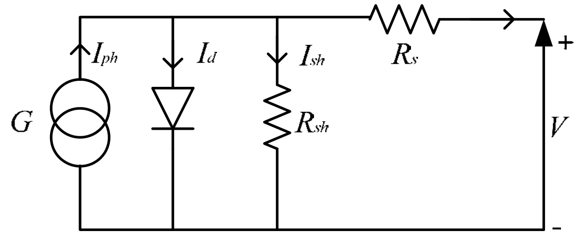


Fig. 1 – *Simplified equivalent circuit PV model.*

Equation (1) is valid for a solar cell. For the exact application of this equation for PV module, the term of $(V+R_sI)/V_t$ is replaced by $(V+R_sI)/N_sV_t$, in which N_s is the number of series connected cells in a PV panel.

The maximum power (P_{mp}) of photovoltaic panel is given by:

$$P_{mp} = V_{mp} I_{mp}\,, \tag{2}$$

where V_{mp} and I_{mp} are the voltage and current at the maximum power output. Other important factors of PV modules are the fill factor [27, 28] and the efficiency [29 – 31] which are used for the evaluation of the PV panel performance, the expressions are given respectively by:

$$FF = \frac{P_{mp}}{V_{oc} I_{sc}}\,, \tag{3}$$

$$\eta = \frac{P_{mp}}{GA}\,, \tag{4}$$

where A is the area of the module [m^2].

Typically N_s cells are connected in series to get the requisite voltage of PV module. All the cells are forced to carry the same current called panel current in series panel. Typically, panel consists of many solar cells, and for each n cells are equipped with one bypass diode, so bypass diode is connected with a string (one string corresponds to n cells in series). Fig. 2 shows the internal construction of the PV panel. It can be seen that there are 36 cells serially connected and is protected by one bypass diode.

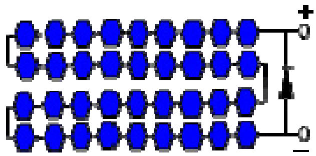


Fig. 2 – *Connection schematic of bypass diodes in the PV module.*

The electrical characteristics specifications under STC form manufacturer are listed in **Table 1**.

Table 1
Template Data of Experimental PV Module.

Silicon type	P_{mp} [W]	I_{sc} [A]	I_{mp} [A]	V_{oc} [V]	V_{mp} [V]	FF	η [%]
Jumao photonics 50	50	3.2	2.9	21.6	17.3	0.72	13.94

To determine the five parameters exist in (1), which are: I_{ph}, R_s, R_{sh}, I_0 and a, you can see [32]. The diagram of the closed loop system for MATLAB® and Simulink is shown in Fig. 3, which includes the electrical circuit of the PV module mono-crystalline. The photovoltaic module is modeled using the electrical characteristics to provide the current and voltage of the photovoltaic module output.

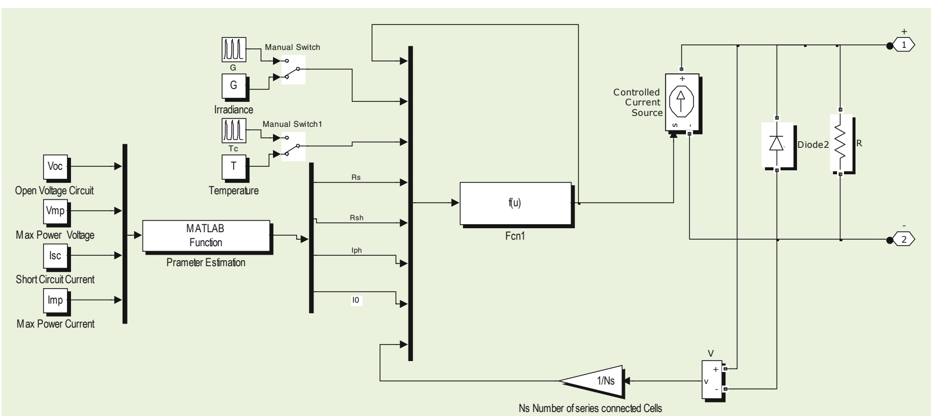


Fig. 3 – *Simulink simulation to illustrate the I-V and P-V module output characteristics.*

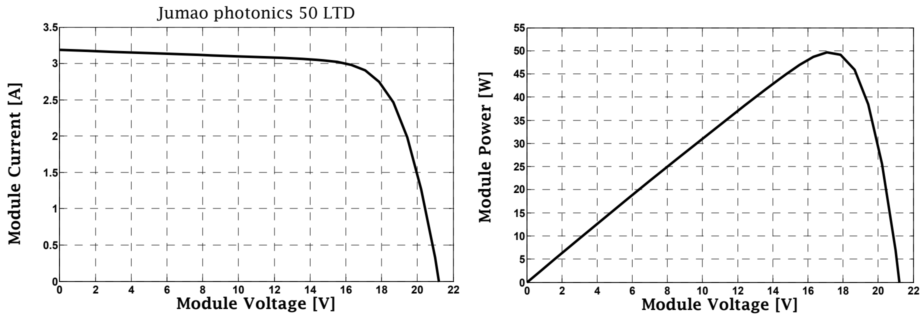


Fig. 4 – *I-V and P-V module under STC (Initial Characteristic).*

3 Experiments and Verification

The outdoor measurements were performed in the site of Applied Research Unit in Renewable Energy (URAER), Ghardaïa, Algeria (latitude 32.49°N, longitude 3.67°E), and Sunlight duration in number of days by year. Experiments were conducted using mono-crystalline PV module (see e.g. Fig.6). Additionally the following meteorological parameters are measured as two minutes averages:

- Solar irradiance measured by a pyranometer (kipp & Zonen^{TM} CMP^{21}) with is also installed on a metal plate, coplanar with the PV field.
- Back of panel is recorded via PT100 resistive thermal sensors.

Fig. 5 shows the evolution of module temperature, ambient temperature and irradiation as function of time.

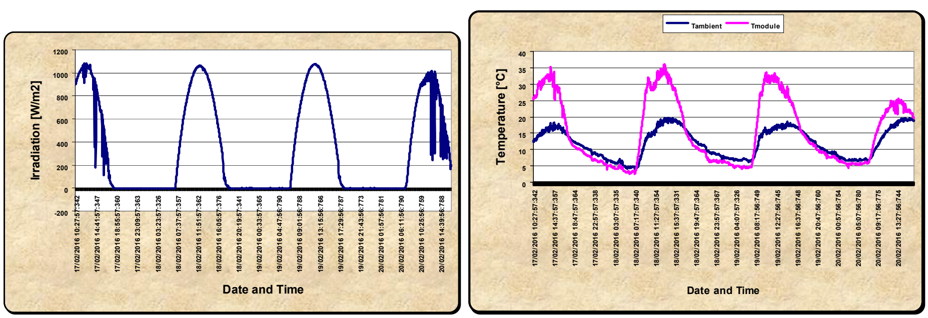


Fig. 5 – *Evolution of Irradiation (Left), module temperature and ambient temperature (Right) as function of time.*
(Colors can be seen in electronic version)

3.1. PV outdoor measurements

One of the objectives of this work is the experimental study of PV modules in real conditions of work. Experimental measurements were taken using the panel connected to the Solmetric I-V Curve Tracer with SolSensor (see Fig.6). It measures the current-voltage (I-V) curves of PV panels and immediately compares the results to the predictions of the built-in PV models.

- Measure the essential parameters for the I-V curve measurements (irradiance, temperature cell and ambient temperature by SolSensor).
- Save the V-I curve data, extract points of interest and store the I-V curves for later analysis. The acquired data are then treated and translated at standard test condition in order to comport with the data sheet of the photovoltaic modules values at standard test condition.

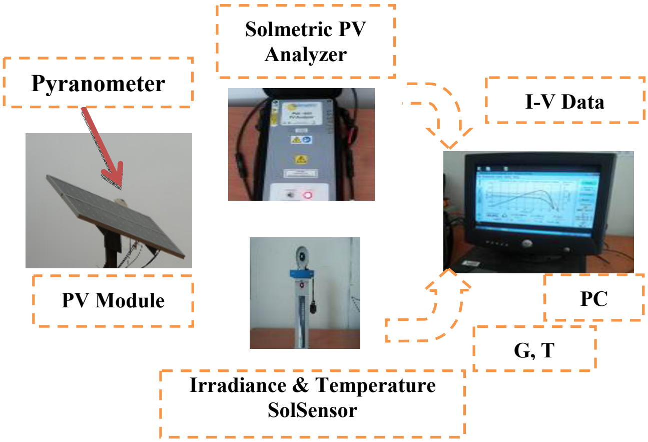


Fig. 6 – *Experimental setup of measurements (03/05/2016).*

Table 2 summarizes the electrical specification of the Solmetric PVA-600 Analyzer.

Table 2
Electrical Specifications of "PVA-600 Analyzer".

Parameters	Range	Accuracy	Resolution
Current (I_{dc})	0 – 20A	±0.5%±0.04 A	2mA
Voltage (V_{dc})	0 – 600V	±0.5%±0.25 V	25mV
Irradiance (G)	0 – 1500W/m^2	±2%	1W/m^2
Temperature (T)	0 – 100°C	Typically less than 2°C	0.1°C
Tilt	0–90° (horizontal)	±1deg (0-45° tilt)	–

The characteristic are visualized with the use of software, Fig. 7 shows the software interface.

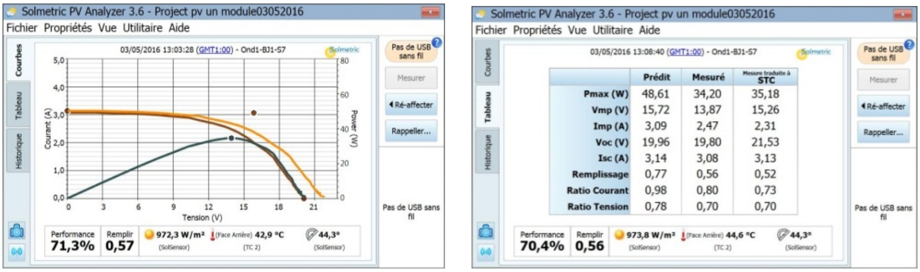


Fig. 7 – *Software interface with an I-V characteristic.*

To evaluation the effectiveness and accuracy of the model, several experiments were conducted. Fig. 8 shows the experimental I-V and P-V curves of the module at difference irradiance values and temperature.

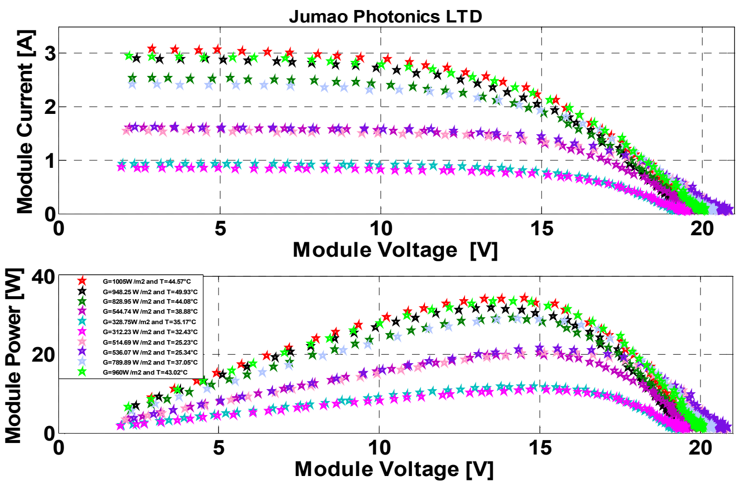


Fig. 8 – *Measured I-V and P-V characteristics under different operating conditions.*
(Colors can be seen in electronic version)

Fig. 9 shows the simulated and experimental results for the module before and after 12 years of continuous exposure on URAER, Ghardaïa site as desert climate. In these study case, the solid lines show simulation curves (before and after exposure) and dashed (stars) lines show measurement curves. These figure show good agreement between measurement curves and simulation curves.

The data of simulation and experimental of the PV module is given in **Table 3**. The term γ (%) in this table is the relative error between simulated and experimental values which is given by [33]:

$$\gamma = \frac{\left| X_{simulation} - X_{Measured} \right|}{X_{Measured}} \times 100\% .$$

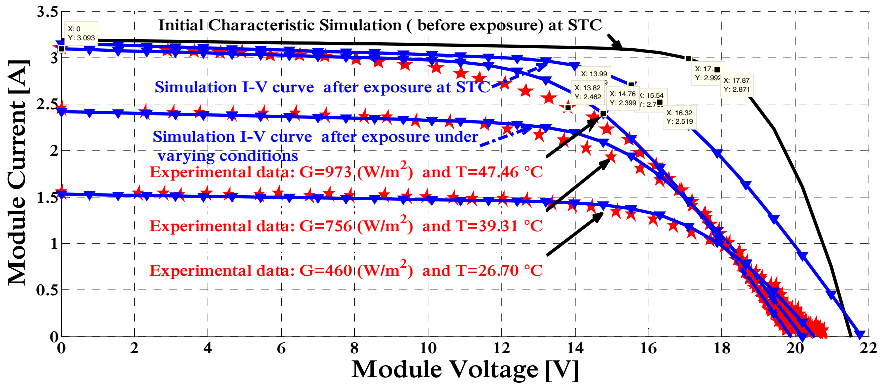


Fig. 9 – *I-V characteristics before and after ageing at STC and operating conditions.*
(Colors can be seen in electronic version)

The index ‘‘Measured” refers to the experimental and the index ‘‘Simulation” refers to the simulation.

Table 3
Data of simulation and experimental of the PV module.

Parameters	I_{mp} [A]	V_{mp} [V]	V_{oc} [V]	I_{sc} [A]	P_{mp} [W]	FF	η [%]
Under Outdoor test $G = 973[\text{W/m}^2]$ $T = 47.46[°\text{C}]$	2.47	13.87	19.80	3.08	34.20	0.56	9.54
Simulation model	2.50	14.37	19.90	3.09	35.92	0.58	10.0
Relative error γ (%)	1.21	3.60	0.50	0.32	4.80	3.45	4.80

As shown in **Table 3**, the relative error γ of the short circuit current and open circuit voltage is below 1%. In addition, the relative error γ of maximum power-output, fill factor and efficiency are below to 4.80%.

4 Evaluation and Analysis of Degradation

The main requirement for a PV module is to obtain the top performance results during the solar energy conversion procedure. On the other hand, efficiencies of the PV modules during real working conditions must be measured in order to rule on the most adapted plan topology. The performance of photovoltaic (PV) modules is greatly influenced by many factors, such as solar insolation, ambient temperature and the time under exposure to the sun, they factors contributes significantly to the final power output. The mode citied below are at the origin of the degradation of the modules, which is manifested in several forms.

4.1 Degradation mode

Table 4 summarizes the degradations modes of the photovoltaic modules existing in reviews literature [20, 34, 35].

Table 4
Degradations modes.

Degradations modes.
Encapsulant delamination
Encapsulant discoloration
Corrosion
Broken cells
Junction box failures
Broken interconnects
Hotspots

4.2 Degradation analysis methodology

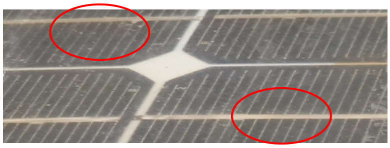
The effect of degradation of photovoltaic solar modules and their subsequent loss of performance has a serious impact on the total output power. According to the literature, there are some methods used to evaluate the photovoltaic modules degradation such as [36 –38]:

- Visual inspection.
- I–V Curves measurement normalized at STC.
- Infrared thermography (IRT).
- Analytical calculations of degradation rates.
- Insulation resistance of all modules in dry and wet condition.
- Cost analysis.

In this paper, the presented study was carried out using Visual inspection, I-V curves measurement normalized at STC by two methods (described in IEC-60891) comported with Solmetric PV Analyzer Data Analysis Tool and calculation of degradation rates.

4.3 Visual inspection

Visual inspection is part of the test described in IEC 61215 [39]. It is the first step to evaluate the degradation modes in photovoltaic modules. The inspection must be executed under real work conditions where PV modules can get good quality solar irradiance. Moreover, reflections should be evaded during the test because it can result in defective images. In order to present the long term degradation of module. The inspection allows detecting some failures after 12 years of exposure in the desert environment that can be observed visually; such discoloration (see Fig. 10).



Interconnect discoloration

Fig. 10 – *Main failures observed of PV module in the site after 12 years of working.*

The main impact of discoloration of the encapsulation is reduction of short circuit current of the panel witch consequently also reduces the power output of the panel PV.

4.4 Translation methods to STC

According to the ICE 60891 standard [40], data measurements were conducted under clear sky conditions with irradiance values greater than 800 W/m^2. It was translated into photovoltaic output characteristics in STC by using translation methods. The object is to translate I-V curves from the real conditions at which they were measured (T_x and G_x) to any another set of conditions (T_2 and G_2). Habitually these second conditions are chosen to be the STC (25°C and 1000 W/m^2) [41]. **Table 5** shows the STC translation equations.

Table 5
Translation Methods to STC.

Translation Methods
I-V curves
IEC 60891 Procedure 1
$I_2 = I_1 + I_{sc,1} \times ((G_2/G_1 - 1) + \alpha(T_2 - T_1))$
$V_2 = V_1 - \beta(T_2 - T_1) - R_s(T_2 - T_1) - KI_2(T_2 - T_1)$
IEC 60891 Procedure 2
$I_2 = I_{sc,1} \times ((G_2/1000) + \alpha(T_2 - T_1))$
$V_2 = V_1 - \beta(T_2 - T_1) - R_s(T_2 - T_1) - KI_2(T_2 - T_1) - V_{oc,1} \times g \times \ln(G_2/G_1)$
$V_{oc,1} = N_s V_t \times \ln(I_{sc,1}/I_{o,x}) + \beta(T_2 - T_1)$ [37].

The Table nomenclature is defined as: K – Curve compensation factor (Ω/°C); α and β – the relative current and voltage temperature coefficients; g – Irradiance correction factor for the V_{oc}.

4.5 Degradation rates

In order to assess the degradation performance of the photovoltaic modules or arrays over its lifetime after a long term exposure to the sun in desert climatic condition, the degradation rate (R_d) and annual degradation (R_{da}) of each parameters such as maximum power (P_{mp}) were determined, and current at the maximum power point (I_{mp}), voltage at the maximum power point (V_{mp}), open circuit voltage (V_{oc}), fill factor (FF) and efficiency η were calculated analytically by following expressions equation [42, 43]:

$$R_d\left(X\right)=\left(1-\frac{X}{X_0}\right), \tag{5}$$

$$X=\left[P_{mp}\ I_{mp}\ V_{mp}\ I_{sc}\ V_{oc}\ FF\ \eta\right],\quad X_0=\left[P_{mp0}\ I_{mp0}\ V_{mp0}\ I_{sc0}\ V_{oc0}\ FF_0\ \eta_0\right],$$

where X_0 represents the reference value of the parameters under STC given by manufacturer and X represents value after degradation,

$$R_d(X)=\frac{R_d}{\Delta T}\quad [\%], \tag{6}$$

where ΔT (years) is the time of exposure under real operating condition.

Fig. 11 shows the Simulink block diagram of simulation methodology. I_{scmes} and V_{ocmes} are the measured short circuit current and open circuit voltage respectively, I_{mpmes} and V_{mpmes} are the measured current and voltage at the maximum power point respectively, G_{STC} and G_{mes} are the reference and measured irradiances.

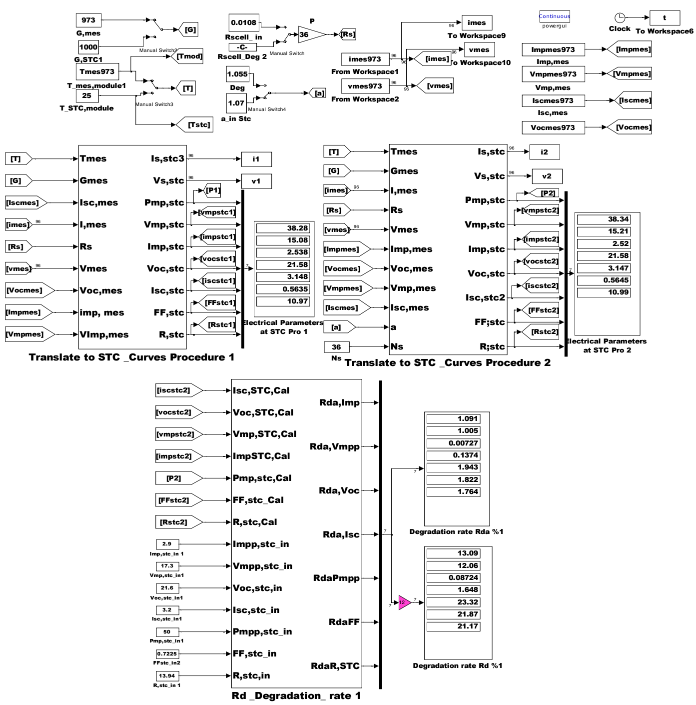


Fig. 11 – *Simulink block diagram of Different Methods to Evaluate the Degradation Rate.*

4.6 Results and discussion

From data measurements, the I-V characteristics of photovoltaic module under test translated to STC by using conversion methods to STC after 12 years of continuous exposure on URAER in the desert region in south of Algeria are illustrated in Fig. 12.

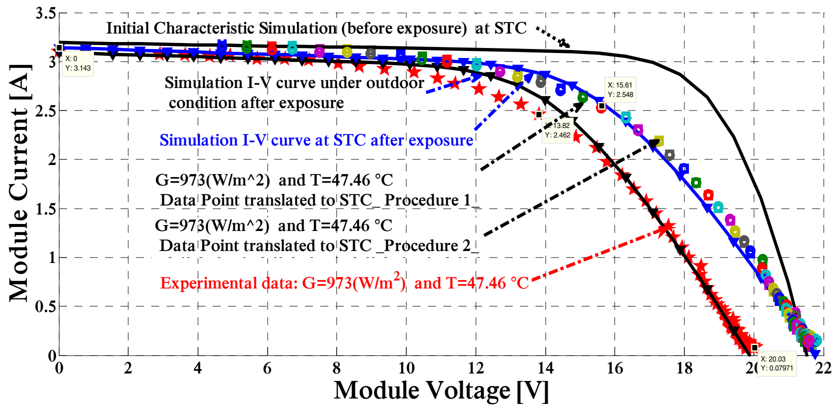


Fig. 12 – *I-V curve of the module translated to STC based on conversion methods and data obtain by the model.*
(Colors can be seen in electronic version)

The results of the translation methods are summarized in **Table 6**. The term γ_1 (%) in this table is the relative error between simulated and experimental values translated to STC which is given by

$$\gamma_1 = \frac{\left| X_{simulation,STC} - X_{PE} \right|}{X_{PE}} \times 100\% .$$

The index ‘‘PE” refers to the Electrical Parameters translated to STC and the index ‘‘Simulation” refers to the simulation.

The deviation of the relative error of the P_{mp}, FF and η is high by using Solmetric PV Analyzer (**Table 6**). It includes various factors that lower solar module output such as: Effects of spectral changes over time, module temperature, effects of reflection by PV incident angles, effects of solar spectrum according to measurements conditions [44, 45]. Thus from the translated I-V data using Procedure 1, 2, and PV Solmetric Analyzer translated, error in the value of P_{mp} was calculated and plotted at different irradiances. Fig. 13 shows the error in P_{mp} at different irradiances for mono c-Si.

According to Fig. 13 the translated by Procedure 1 and PV Solmetric are not suited for making large irradiance translations that differ from the measured value more than 20%. The procedure 2 yields more accurate results for larger irradiance corrections [20].

Table 6
Data Translation to STC of the PV module.

Parameters	I_{mp} [A]	V_{mp} [V]	V_{oc} [V]	I_{sc} [A]	P_{mp} [W]	FF	η [%]
Under Outdoor test G=973W/m^2 T=47.46 °C	2.47	13.87	19.80	3.08	34.20	0.56	9.80
After exposure at STC (Simulation)	2.54	15.63	21.65	3.143	39.70	0.58	11.07
Relative error γ [%]	-1.21	-3.60	-0.50	-0.32	-4.80	-3.45	-4.80
Procedure 1	2.538	15.08	21.58	3.148	38.28	0.57	10.97
Relative error γ_1 [%]	0.078	3.64	0.32	-0.16	3.70	0.03	0.066
Total Relative Error γ_1+γ [%]	-1.13	-0.04	-0.18	-0.48	-1.10	-3.42	-4.73
Procedure 2	2.52	15.21	21.58	3.147	38.34	0.57	10.99
Relative error γ_1 (%)	0.793	2.76	0.32	-0.16	3.54	0.03	0.007
Total Relative Error γ_1+γ [%]	-0.42	-0.84	-0.18	-0.48	-1.25	-3.42	-4.79
Solmetric PV Analyzer translated	2.31	15.26	21.53	3.13	35.18	0.52	10.08
Relative error γ_1 [%]	9.95	2.42	0.56	0.41	12.84	11.5	9.82
Total Relative Error γ_1+γ [%]	8.74	1.17	0.06	0.09	8.05	8.09	5.02

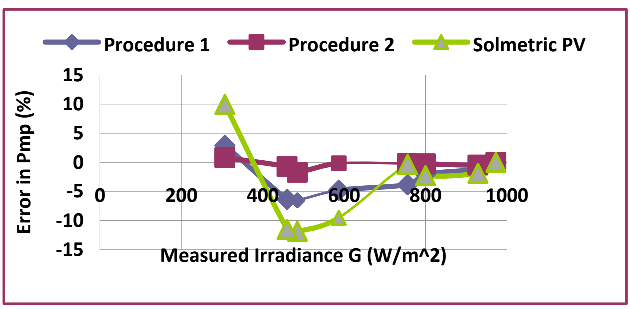


Fig. 13 – *Error in P_{mp} at different irradiances.*
(Colors can be seen in electronic version)

A comparison between the values given by manufacturer (see **Table 1**), data measurement obtained after translation in Standard Test Condition (Procedure 1, 2) data translated using Solmetric PV Analyzer and Data calculated by simulation model. **Table 7** shows the values of degradation rates (R_d) and annual degradation of the module electrical performances at STC, considering measurements at 03.05.2016.

Table 7

Degradation rate (R_d) *and Annual Degradation* (R_{da}).

Parameters	I_{mp} [A]	V_{mp} [V]	V_{oc} [V]	I_{sc} [A]	P_{mp} [W]	FF [%]	η [%]
R_d Pro1 [%]	12.49	12.81	0.098	1.633	23.45	22.00	21.30
R_d Pro 2[%]	13.09	12.06	0.087	1.648	23.82	21.87	21.17
R_d Simulation [%]	12.41	9.65	0.23	1.78	20.60	19.72	20.60
R_d Sol PV [%]	20.34	11.79	0.324	2.19	29.64	28.03	27.69
R_{da} Pro1 [%]	1.04	1.068	0.0081	0.136	1.95	1.83	1.75
R_{da} Pro 2[%]	1.09	1.005	0.0072	0.137	1.94	1.82	1.76
R_{da} Simulation [%]	1.03	0.80	0.02	0.15	1.71	1.64	1.72
R_{da} Sol PV [%]	1.70	0.98	0.027	0.18	2.47	2.34	2.30

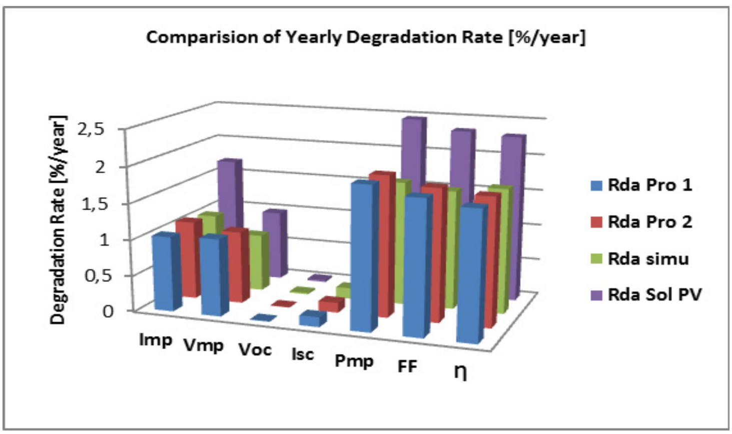


Fig. 14 – *Degradation rate of IV parameters for PV module for outdoor exposure test after 12 years of operating.*
(Colors can be seen in electronic version)

Fig. 14 displays the yearly degradation rates of I_{mp}, V_{mp}, V_{oc}, I_{sc}, P_{mp}, FF, and η for the module. The first observation, we can report a decrease in the P_{mp}, V_{mp}, I_{mp}, FF and η. Surely, the increase in R_s has principally contributed in the performances degradation of tested photovoltaic module, its study and understanding is important in order to find solutions for the decrease of the output power of PV modules [46]. From Fig. 12 it can be seen that the R_s affects the slope of the IV characteristics, by reducing voltage output (ΔV), fill factor (FF) and hence the efficiency of the module [46].

Series resistance increase could arise from three interfaces/contacts:

- Cell and Metallization contact.
- Metallization and Ribbon contact.
- Ribbon and Ribbon contact.

5 Standard Uncertainties and Uncertainty Analysis

The International Guidelines of Uncertainty in Measurement (GUM) [23] are used for calculating the combined uncertainty of the corrected power P_{STC}. The GUM technique employs two types of uncertainty estimates: type A and Type B. This paper describes a method for calculating estimated measurement uncertainties of P_{STC} data obtained by Solmetric I-V Curve Tracer. Uncertainty in field measurement is a result of SolSensor (irradiance and temperature), equipment installation, translation methods, and the environmental conditions at the site where the experimentation is used.

The GUM steps to evaluating overall uncertainty of a measurement can be summarized in five steps [47]:

Sources of uncertainties

- Obtained from manufacturers specifications, from past experience of the measurement, from calculations and from calibration certificates.

Standard Uncertainty (u)

- Calculated using expanded uncertainty and statistical distribution (type A), and/or Non-statistical distribution (type B).
- The expressions of the standard uncertainty of the both type A and type B are given respectively by: $u_A = \sigma/\sqrt{n}$ or $u_A = U/k$ (σ – standard deviation, n – Number of readings, U – expanded uncertainty and k – coverage factor), $u_B = U/\sqrt{3}$ (rectangular distribution).

Sensitivity Coefficient (*c*)

- Calculated using partial derivative from the measurement equation for each input variable.

Combined Uncertainty

- Calculate the combined standard uncertainty time using the root-sum-of-squares method for all standard uncertainties time in step 2, 3.
- The expression is given by: $u_c = \sqrt{\sum_{j=0}^{n-1} (u \times c)^2}$.

Expanded Uncertainty (U_{95})

- Calculate the expanded uncertainty by multiplying the combined standard uncertainty time by the coverage factor ($k = 1.96$ for a 95% confidence interval).
- The expression is given by: $U_{95} = k \times u_c$.

5.1 Uncertainty calculation

Quantification of uncertainty is an obligation for calibration measurements. It is critical for all power measurements systems to gain a proper understanding of the influence of factors such as uncertainties on measured values (current and voltage), sensor uncertainties for irradiance and temperature, uncertainty in corrections to STC.

The electrical parameters at STC are derived from measurement and translation procedure. Consequently the uncertainty in the STC data is composed of the actual measurement uncertainties introduced by the instrument plus the uncertainties in the temperature coefficients which are used in the translation equations (Fig. 15).

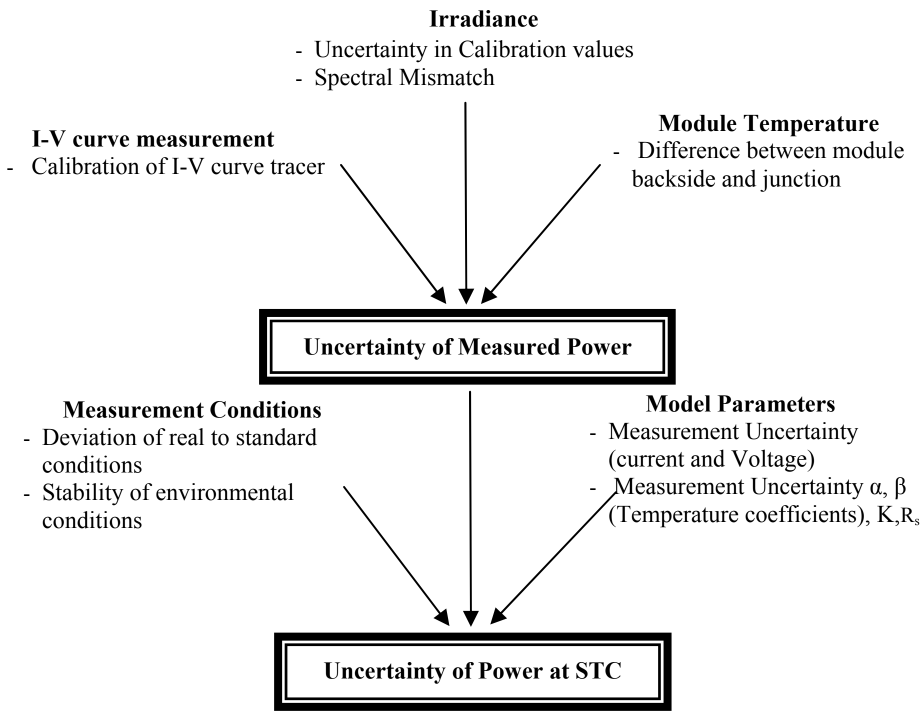


Fig. 15 – *Major influences on the combined uncertainty of power at STC [48].*

4.1. Uncertainties in measurements

The method in GUM [23] is used to calculate the uncertainty contributions of the corrected power (P_{STC}). In **Table 8**, we have listed an uncertainty for the measurement parameters.

Table 8

Source of uncertainties that contribute to the measurement uncertainty.

Parameters	Quantity	Standard Uncertainty (u)	Expanded Uncertainty (U)
Current	(I_{dc})	$U/\sqrt{3} = 0.29\%$	0.5%
Voltage	(V_{dc})	$U/\sqrt{3} = 0.29\%$	0.5%
Irradiance	(G)	$U/\sqrt{3} = 1.15\%$	2%
Temperature	(T)	$U/\sqrt{3} = 1.15\%$	2°C

According to [48] the estimated of parameters uncertainties of the correction parameters is summarized in **Table 9**. For plus details of the calculated of uncertainties parameters correction see [48].

Table 9

Estimated parameters correction uncertainties for the crystalline silicon.

Parameters	Quantity	Standard Uncertainty (u)	Expanded Uncertainty (U)
Current Temperature coefficient	(α)	$U/\sqrt{3} = 0.073\%$	0.063%/°C×2°C
Voltage Temperature coefficient	(β)	$U/\sqrt{3} = 0.445\%$	0.385%/°C×2°C
Curve compensation factor	(K)	$U/\sqrt{3} = 0.096\%$	0.08316%/°C×2°C
Series resistance	(R_s)	$U/\sqrt{3} = 4.04\%$	7%

The algorithm has been implemented in Matlab program that automatically calculates the expanded uncertainties in power at STC (Fig. 16).

The major contributions to the uncertainty of the power at STC determined by field I-V curve measurements were presented. The expanded uncertainty with 95% confidence in the maximum power is listed in **Table 10**.

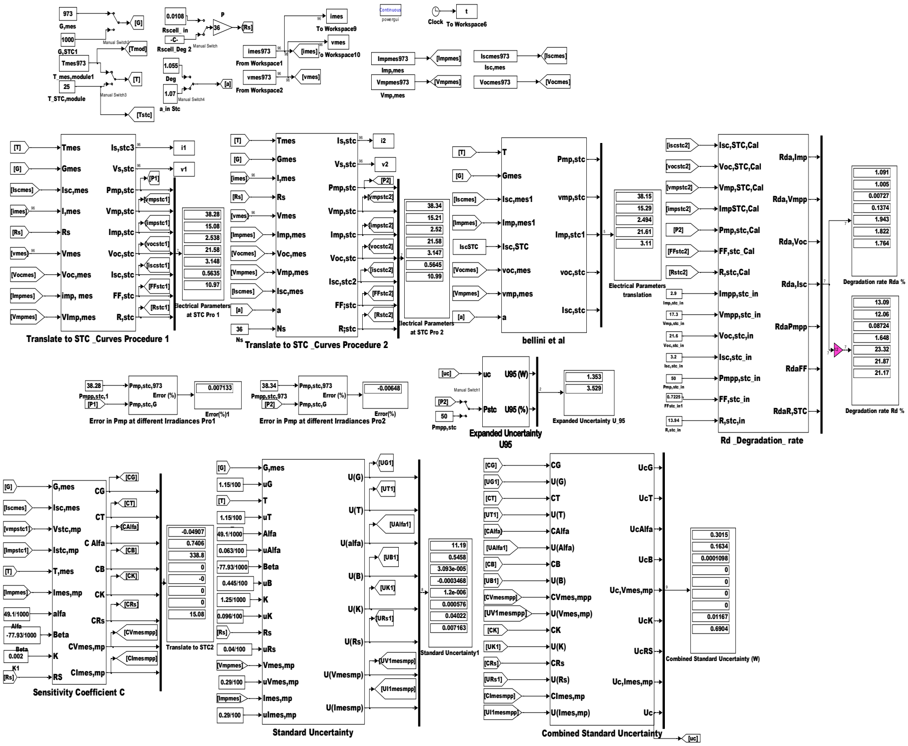


Fig. 16 – *Methodology user defined subsystem block.*

Table 10

The expanded uncertainty in the maximum power.

The expanded uncertainty			
G = 800 W/m^2 and T = 44.9°C		973 W/m^2 and T = 47.46°C	
$U_{P_{mp}}$ Pro 1	$U_{P_{mp}}$ Pro 2	$U_{P_{mp}}$ Pro 1	$U_{P_{mp}}$ Pro 2
3.21	3.34	3.53	3.56

6 Conclusion

The objective of this paper is to present the effect of the real outdoor conditions on the photovoltaic modules performance in the desert environment after a long term exposure of more than 12 years using Solmetric PV Analyzer. A general approach on modeling and simulation of PV module has been presented.

Various translation procedures available in the literature were examined, and decision was made to use procedure**s** 1 and 2 of IEC 60891 for translating the field I-V data to the STC. MATLAB/SIMULINK software has been developed to implement these procedures.

There was visual degradation and relative differences between the electrical parameters of the PV module given by manufacturers and investigated after 12 years of exposure in desert environment.

The observed results lead to the following conclusions:

- Maximum power losses (>20%) are attributed generally to FF losses (series resistance increase);
- The maximum power degrades 2%/year average;
- The module efficiency also showed a significant degradation under real outdoor conditions.

The uncertainties relate typically to the evaluation of the solar resource and to the performance of the system itself. We have calculated the uncertainty in the data by using the International Guidelines of Uncertainty in Measurement (GUM). The uncertainties introduced in translating the P_{mp} depending on the environment conditions.

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