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Degradation Evaluation of PV Module Using Solmetric PVA-600 Analyzer

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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 out put from the module. As the output reduces each year. The degradation is also assessed using I-V characteristics translated at Standard Test Conditions (STC) conditions compared with nominal STC data given by the manufacturer. This paper presenter an evaluation of degradation in PV module after a long term exposure of more than 12 years, this evaluation uses tow methods: Visual inspection of degradation of the Jumao photonics 50 LTD module and data given by Solmetric PVA-600 Analyzer translated at STC .Finally, the degradation rates calculated for the electrical parameters. The degradation of maximum output current is about 1.06%/year. The degradation rate of maximum output voltage is 1.47%/year. The degradation rate of open-circuit voltage is 0.46%/year. Degradation of short-circuit current is about 0.18%/year. The degradation of maximum power out put is 2.33%/year. The degradation of fill factor is 1.76%/year. The degradation of efficiency is 2.32%/year.**

***Keywords*— Photovoltaic Module, Translation, Solmetric PVA-600 Analyzer, Visual inspection, Degradation Rate.**

I. 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 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].

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 [14]. The main objective of this paper is to provide a comprehensive analysis of the degradation rates of PV module in desert environment of Ghardaïa (Algeria) using Solmetric I-V Data Analysis Tool.

II. 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 [15, 16].

A. Model of Practical PV

Modeling needs two steps; the first step is parameters estimation, and the second is to use these estimated parameters within the modeling equations that produce the curve illustrating the behavior of the panel under varying conditions (temperature and irradiance).

Forward Characteristics

Photovoltaic (PV) arrays are built up with combined series/parallel combinations of PV solar cells [17], 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 [16].

$$I = I_{ph} - I_0\left[\exp\left(\frac{V+IR_s}{V_t}\right)-1\right]-\frac{V+IR_S}{R_{sh}}. \qquad (1)$$

Where

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

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

$$R_{sh} = R_{sh,STC}\frac{G}{G_{STC}}$$

$$R_s = R_{s,STC}\ .$$

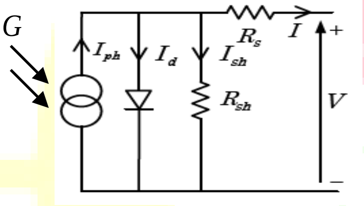


Fig. 1 Simplified equivalent circuit PV model.

Where $V_t = aKT_c/q$ is the thermal voltage ,q is the electron charge (1.602×10^{-19} C), K is the Boltzmann constant (1.38×10^{-23} J/K), 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} the series and shunt resistance respectively, T_c is the reference cell operating temperature (25°C), V is the cell output voltage, Volts, 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 .

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

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

$$P_{mp} = V_{mp} I_{mp} \qquad (2)$$

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 [18, 19], and the efficiency [20–22], which are used for the evaluation of the PV panel performance, the expressions are given respectively by:

$$FF = \frac{P_{mp}}{V_{oc} I_{sc}} \qquad (3)$$

$$\eta_{mp} = \frac{I_{mp} V_{mp}}{G.A} \qquad (4)$$

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.

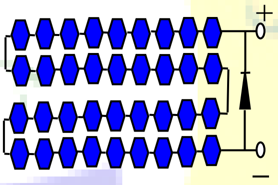


Fig. 2 Connection schematic of bypass diodes in the PV module (Jumao photonics 50 LTD).

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

TABLE I

TEMPLATE DATA OF EXPERIMENTAL PV MODULE

Silicon type	P_{mp} (W)	I_{sc} (A)	I_{mp} (A)	V_{oc}(V)	V_{mp} (V)	FF (%)	N_s	η (%)
Jumao photonics 50 LDT	50	3.2	2.9	21.6	17.3	72.25	36	13.94

Five unknown parameters exist in (1), which are: I_{ph} , R_s , R_{sh} , I_0 and a. Our main objective is to determine the five parameters only based on the available data in a PV panel datasheets.

B. Parameter Estimation

In this section a method for approximating the five parameters in the five parameter one diode model is outlined. The approximation technique does not include estimate of ideality factor. All the other parameters are resolute by iteration based on the datasheet values and an assumed value of the ideality factor. The derived equations used in this method [23, 26] are as follows:

$$I_0 = \frac{I_{sc}}{\exp\left(\frac{V_{oc}}{N_s V_t}\right) - 1} \quad (5)$$

$$R_s = \frac{V_{mp}}{I_{mp}} - \frac{N_s V_t R_{sh}}{I_0 R_{sh} \exp\left(\frac{V_{mp} + I_{mp} R_s}{N_s V_t}\right) + N_s V_t} \quad (6)$$

$$R_{sh} = \frac{V_{mp} + I_{mp} R_s}{I_{ph} - I_{mp} - I_0\left[\exp\left(\frac{V_{mp} + I_{mp} R_s}{N_s V_t}\right) - 1\right]} \quad (7)$$

$$I_{ph} = \frac{R_s + R_{sh}}{R_{sh}} I_{sc} \quad (8)$$

Uses iterative solution of equations to obtain the parameters, iteration is a decent way to find values that fits well and gives a small error. In [24] it is recommended to iterate the parameters and minimize the error values given in equation (12).

$$E_1 = \frac{V_{mpp}}{I_{mpp}} - \frac{N_s V_t R_{sh}}{I_0 R_{sh} \exp\left(\frac{V_{mpp} + I_{mpp} R_s}{N_s V_t}\right) + N_s V_t} - R_s \quad (9)$$

$$E_2 = \frac{V_{mpp} + I_{mpp} R_s}{I_{ph} - I_{mpp} - I_0\left[\exp\left(\frac{V_{mpp} + I_{mpp} R_s}{N_s V_t}\right) - 1\right]} - R_{sh} \quad (10)$$

$$E_3 = \frac{R_s + R_{sh}}{R_{sh}} I_{sc} - I_{ph} \quad (11)$$

$$E = E_1^2 + E_2^2 + E_3^2 \quad (12)$$

A program is developed in MATLAB to implement the parameter estimate algorithm using the equations above.

The solution obtained is given in Tables II.

TABLE II

PARAMETERS ESTIMATION

Parameter	Estimated value
R_s (Ω)	0.3870
R_{sh} (Ω)	195.1494
I_0 (A)	4.6559×10^{-8}
I_{ph} (A)	3.2

III. SIMULATION SOLAR PV

The diagram of the closed loop system for MATLAB® and Simulink is shown in Figure 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.

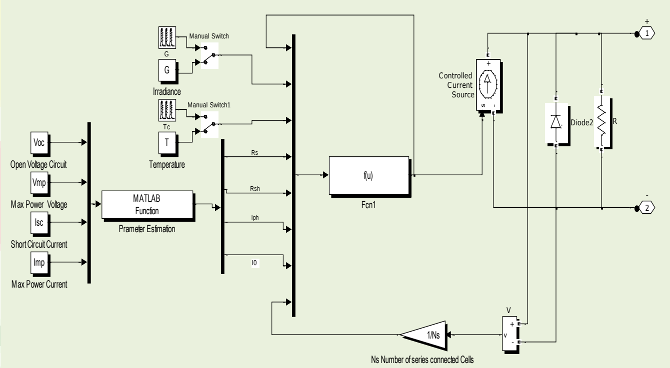


Fig.1 Simulink simulation to illustrate the I-V and P-V module output characteristics.

Fig. 4 shows the simulation of P–V and I–V characteristics (Jumao photonics 50 LTD).

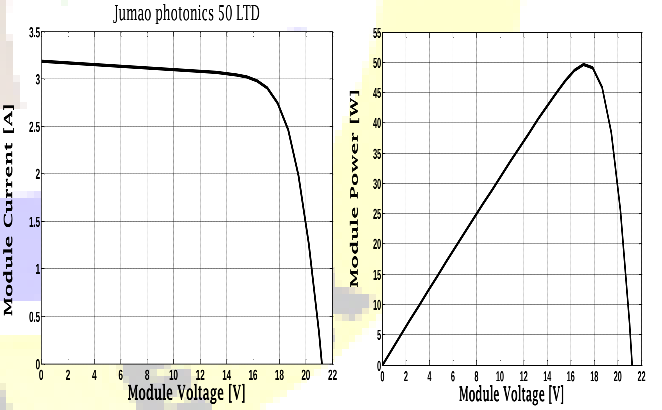


Fig. 2 I-V and P-V module of Jumao photonics 50 panel under STC conditions.

IV. 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: 77 %.

Experiments were conducted using mono-crystalline PV module.

A. 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 Solmetic I-V Curve Tracer with SolSensor (see Fig.5). 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 (STC) in order to comport with the datasheet of the photovoltaic modules values at standard test condition (Fig.6).

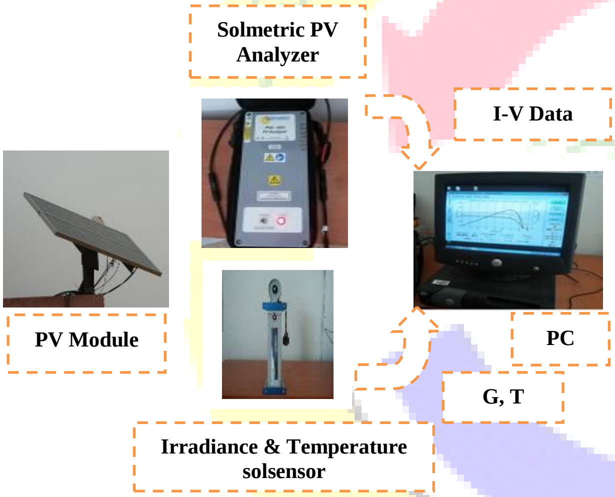


Fig. 5 Experimental setup of measurements (03/05/2016).

The characteristic are visualized with the use of software, Fig .6 shows the software interface.

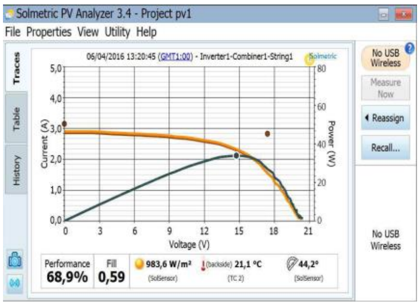


Fig. 6 Software interface with an I-V characteristic.

Fig.7 shows the experimental I-V and P-V curves of the Jumao photonics 50 LTD module at difference irradiance values and temperature.

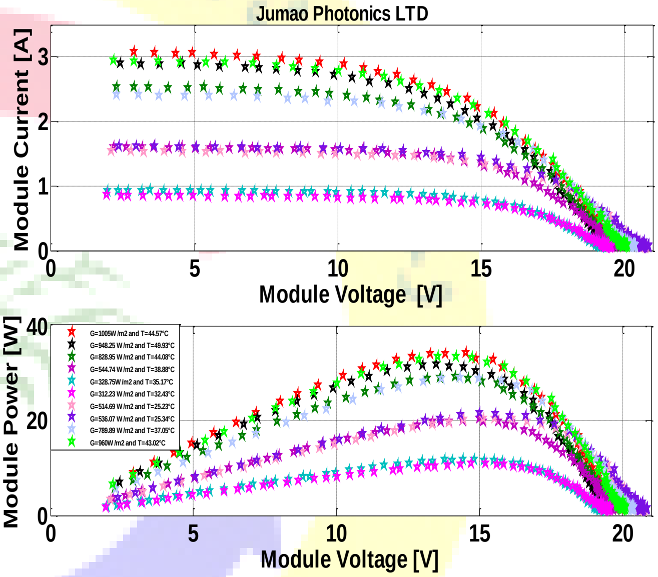


Fig.7 Measured I-V and P-V characteristics under different operating conditions.

V. 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 plant 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.

A. Degradation mode

Table III summarizes the degradations modes of the photovoltaic modules existing in reviews literature [27–32].

TABLE III

DEGRADATIONS MODES

Encapsulant delamination
Encapsulant discoloration
Corrosion
Glass breakage
Broken cells
Junction box failures
Broken interconnects
Backsheet cracking
Hotspots
Bypass diode failure
Solder Bond Failure
Open circuits leading to arcing

B. *Degradation analysis methodology*

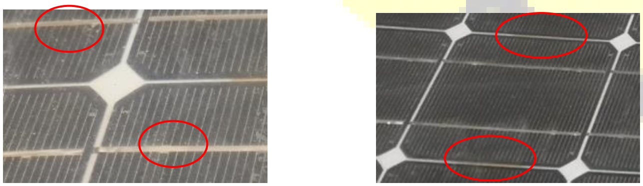
The effect of degradation of photovoltaic solar modules and their subsequent loss of performance has a serious impact on the total output power. According to the literature, there are some methods used to evaluate the photovoltaic modules degradation such as [33–37]:

- Visual inspection.
- I–V Curves measurement normalized at STC condition.
- Infrared thermography (IRT).
- Analytical calculations of degradation rates.

In this paper, the presented study was carried out using Visual inspection, Solmetric I-V Data Analysis Tool and calculation of degradation rates.

C. *Visual inspection*

Visual inspection is part of the test described in IEC 61215 [38]. It is the first step to evaluate the degradation modes in photovoltaic modules [39]. In order to present the long term degradation of Jumao photonics 50 LDT module. The inspection allows detecting some failures after 12 years of exposure in the desert environment that can be observed visually; such discoloration and delamination (see fig.8).



Interconnect discoloration

Encapsulant delamination

Fig.8 Main failures observed of PV module in the site after 12 years of working.

D. *Translation methods to STC condition*

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 method. 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].

E. *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.

We determined the degradation rate (R_d) and annual degradation (R_{da}) of each parameters such as maximum power (P_{mp}), 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]:

$$R_d(X) = \left(1 - \frac{X}{X_0}\right) \times 100 \qquad (13)$$

Where $X = \left[P_{mp} \quad I_{mp} \quad V_{mp} \quad I_{sc} \quad V_{oc} \quad FF \quad \eta\right]$: after degradation.

$X_0 = \left[P_{mp0} \quad I_{mp0} \quad V_{mp0} \quad I_{sc0} \quad V_{oc0} \quad FF_0 \quad \eta_0\right]$: represents the reference value of the parameters under STC given by manufacturer.

$$R_{da}(X)(\%) = \frac{R_d}{\Delta T} \qquad (14)$$

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

Fig.9 shows the Simulink block diagram of simulation methodology.

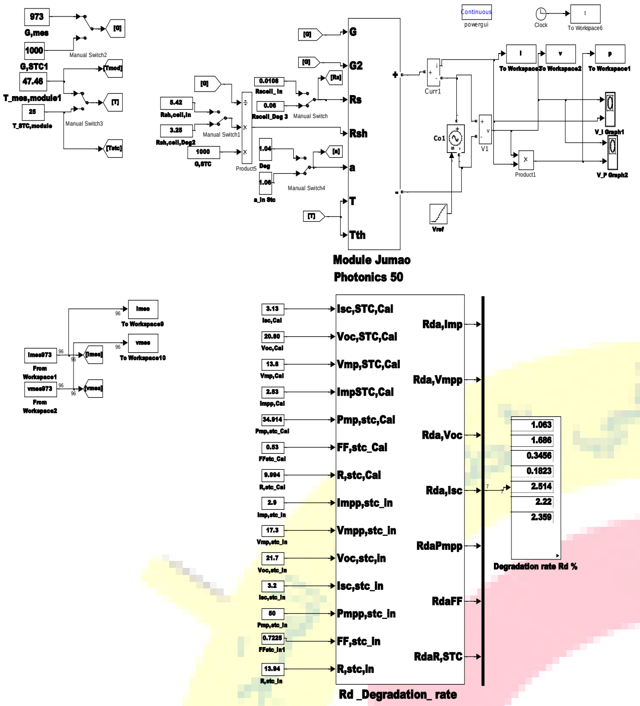


Fig. 9 Methodology user defined subsystem block.

F. *Results and discussion*

From data measurements, the I-V characteristics of photovoltaic module under test translated to STC using Solmetric I-V Data Analysis Tool. Figure 10 shows the IV characteristics of Jumao photonics 50 PV module under STC after 12 years of continuous exposure on URAER in the desert region in south of Algeria.

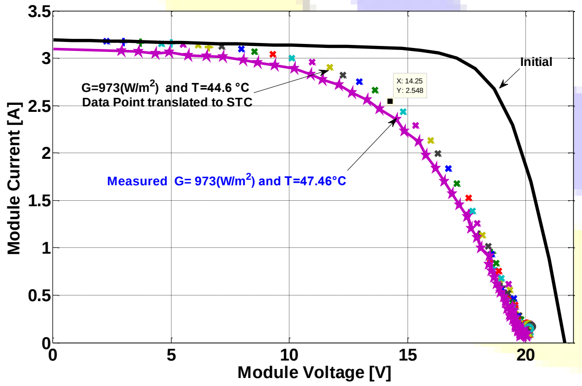


Fig. 10 I-V curve of Jumao photonics 50 LDT PV before and after ageing at STC conditions.

Table IV summarizes the results given by Solmetric I-V Data Analysis Tool.

TABLE IV

TEMPLATE DATA OF EXPERIMENTAL PV MODULE

Parameters	P_{mp} (W)	I_{sc} (A)	I_{mp} (A)	V_{oc}(V)	V_{mp} (V)	FF (%)	η (%)
Under Outdoor test G=973(W/m2)	34.20	3.08	2.47	19.80	13.87	56	9.87
Solmetric data PV tran (STC)	36.05	3.13	2.53	20.40	14.25	57	10

A comparison between the values given by the manufacturer (see table .I) and data translated using Solmetric PV Analyzer. Table VI shows the values of degradation rates (R_d) and annual degradation rates (R_{da}) of the module electrical performances at STC, considering measurements at 03.05.2016.

TABLE V

DEGRADATION RATE (R_D) AND ANNUAL DEGRADATION RATE (R)

Parameters	R_d Sol PV (%)	R_{da} Sol PV (%)
I_{mp} (A)	12.75	1.06
V_{mp} (V)	17.63	1.47
V_{oc} (V)	5.55	0.46
I_{sc} (A)	2.19	0.1825
P_{mp} (W)	28.00	2.33
FF	21.10	1.76
η(%)	27.90	2.32

Fig. 11 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. From Figure 10 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 [44, 46].

Series resistance increase could arise from three interfaces/contacts:

- Cell and Metallization (C/M) contact
- Metallization and Ribbon (M/R) contact
- Ribbon and Ribbon (R/R) contact

The power loss in the module by (28.00% and 2.33%/year) is due to decrease of current and voltage in the module. The current (I_{mp}) and voltage (V_{mp}) loss in the module by (12.75% and 1.06%/year), (17.63% and 1.47%/year) respectively is due to the increases of R_s. The current (I_{sc}) and voltage (V_{oc}) loss in the module by (2.19% and 0.1825%/year), (5.55% and

0.46%/year) respectively is due to the degradation of the optical properties (I_{sc}).The Fill factor and η of the module loss by (21.10% and 1.76%/year), (27.90% and 2.32%/year) respectively.

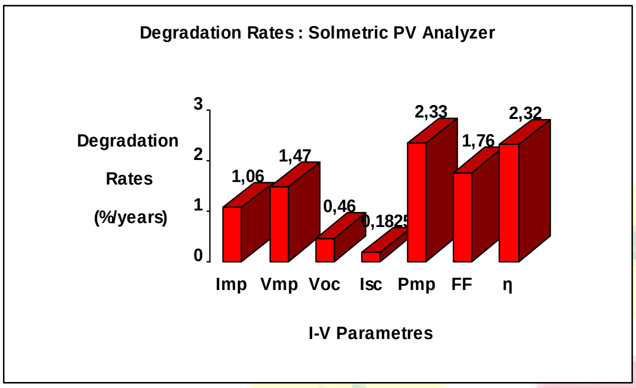


Fig. 11. Yearly degradation rate of IV parameters for PV module for outdoor exposure test after 12 years of operating.

VI. CONCLUSIONS

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.

The observed results lead to the following conclusions:

- maximum power losses (>30%) are attributed generally to FF losses (series resistance increase),
- the maximum power degrades by 2.51%per year,
- the module efficiency also showed a significant degradation under real outdoor conditions.

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