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# Characterization of degradation and evaluation of model parameters of amorphous silicon photovoltaic modules under outdoor long term exposure

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ABSTRACT

The analysis of the degradation of thin-film single junction a-Si PV (photovoltaic) modules and its impact on the output power of a PV array under outdoor long term exposure located in Jaén (Spain), a relatively dry and sunny inland site with a Continental-Mediterranean climate is addressed in this paper. Furthermore, a new procedure of solar cell model parameters extraction experimentally validated is presented. The parameter extraction procedure allows obtaining main model parameters of the solar cells forming the PV array from monitored data of the PV system in real operation of work. Results obtained of the evolution of each one of the solar cell model parameters along the PV system outdoor long term exposure campaign are analysed in order to achieve a better understanding of the performance changes of the PV modules and the behaviour of the output power of the PV array.



## 1. Introduction

The PV (photovoltaic) market continues to grow steadily worldwide. PV systems are replacing conventional energy sources becoming a major source of power generation due to their environment friendly and renewable nature [1].

PV modules are a key element of PV systems and allow conversion of solar energy directly into electrical energy. Several factors influence their performance such as solar irradiance and its spectral distribution [2], mismatches, soiling [3] and operating module temperature [4–7]. Moreover, PV modules tend to degrade after long term outdoor exposition. The degradation rate is mainly associated to the PV module technology and several studies have reported analysis of outdoor performance and degradation of PV modules of different technologies [8–11].

Crystalline silicon (c-Si) and polycrystalline PV modules supply most part of the global photovoltaic energy production with a 90% of the total annual production in 2013, while thin-film (TF) PV modules are in third position with a 10% of market share [12]. TF PV modules use materials such as amorphous silicon (a-Si), CdTe, CIGS (copper indium gallium selenide sulfide) and CIS (copper indium diselenide) among others. The main advantages of TF PV modules are their lower production costs and lower temperature coefficients relative to the c-Si and polycrystalline PV modules. However, TF PV modules present higher degradation rates than polycrystalline and c-Si [9,13]. Recently, the TF a-Si PV modules market share noted a regression probably due to this fact and to their lower module conversion efficiency [12]. Additionally, problems related to the bankability of these technologies still persist.

The a-Si PV modules present LID (light-induced degradation) due to the SWE (Staebler-Wronski effect) [14–17]. The electrical performance degradation of these modules is very important during the initial exposure to outdoor light due to changes in

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photoconductivity and dark conductivity. This effect gradually tends to stabilize at power rates ranging from 10% to 30% of the nominal power of the PV module. However, thermal annealing of the a-Si for several hours at 150 °C reverses these effects [17]. Moreover, a lower temperature annealing also allows recovering the initial performance but takes a longer amount of time [19,20].

Several works have been conducted in attempt to explain the real performance characterization of the a-Si PV modules when deployed outdoors. The degradation rate can be based on the comparison of the monitoring outdoor performance with the initial indoor measurements taken as references [21–24], or by applying LR (Linear Regression) and CSD (Classical Seasonal Decomposition) methods with temperature correction [25,26].

The studies presented in Refs. [22–24] demonstrate that TF hydrogenated single-junction amorphous silicon (a-Si:H) PV modules are degraded mainly by the SWE effect, when compared to other TF technologies. This degradation affects especially the internal parameters of the solar cell as the short circuit current, ideality factor, saturation current and series and shunt resistances [18,27].

Understanding the origin of these degradation modes and how they affect the performance of PV modules is essential to improve the reliability of PV modules, and selecting the best technology for each specific climatic condition. In this paper we analyse the behaviour of TF a_Si PV modules under outdoor long term exposure in Jaén (Spain, Latitude: 37° 47′ 14.35″ N, Longitude: 3° 46′ 39.73″ W, Altitude: 511 m), a relatively dry and sunny inland site with a Continental-Mediterranean climate. The period under scrutiny ranges from late July 2011 to October 2014.

On the other hand, the variation of main solar cell model parameters is also evaluated by means of parameter extraction techniques. We present a new parameter extraction procedure to obtain main model parameters of the solar cells forming the PV system. The parameter extraction has as input the daily monitored data of the PV system in real operation of work and calculates the temporal evolution of main solar cell model parameters.

The paper is organized as follows: An overview of the degradation analysis methodology and parameter extraction technique followed in the study is given in Section 2. Section 3 describes the PV array used in this study and details of the monitoring system. The results and discussion are presented in Section 4. Finally, the conclusions of the study are given in Section 5.

## 2. Methodology

### 2.1. PV array model

The PV array output is based in the well-known “five parameter” model of the solar cell in which the relationship between output current and voltage is given by the following nonlinear implicit equation [28–30]:

$$I = I_{ph} - I_O\left[exp\left(\frac{V+R_sI}{nVt}\right)-1\right]-\frac{V+R_sI}{R_{sh}} \tag{1}$$

where the five solar cell model parameters are: Photocurrent $I_{ph}$; diode reverse saturation current $I_o$; ideality factor $n$; $R_s$ and $R_{sh}$ the series and shunt resistances respectively. I and V are the output current and voltage and $Vt$ is the thermal voltage.

Eq. (1) can also be written as follows,

$$I = I_{ph} - I_d - I_{sh} \tag{2}$$

where $I_d$ and $I_{sh}$ are the currents across the diode and shunt resistance respectively.

Generally, PV modules are formed by parallel strings of solar cells connected in series. However, at present most PV modules include one single string of solar cells. Therefore, the model of the solar cell can be scaled up to the model of the PV array taking into account the configuration of the PV array: Number of PV modules connected in series by string and the number of parallel strings forming part of the PV array as well as the internal configuration of the PV module.

Several studies based on the simulation of PV systems applying this model were reported in the literature. The simulations were carried out in software environments as: Pspice [30–33], Matlab [34–36], or LabView [37,38] and results obtained were experimentally validated with success. In this study we have used Matlab/Simulink for the simulations and the parameter extraction.

### 2.2. Parameter extraction technique

One of the objectives of this work is the investigation of the variation of the solar cell model parameters for single junction a-Si PV modules in real conditions of work. Therefore, this study includes parameter extraction technique in order to find the set of solar cell model parameters able to reproduce the actual behaviour of the whole photovoltaic system with a good accuracy degree.

Monitored electrical parameters: Current, voltage and power at the DC output of the PV array together with in-plane irradiance ($G$) and cell temperature ($T_c$) profiles are needed in order to estimate the set of model parameters of the solar cells forming the PV array.

Considering the number of parallel strings of solar cells present in the PV array, $N_p$, Eq. (2) becomes:

$$I = N_p\left(I_{ph} - I_d - I_{sh}\right) \tag{3}$$

where $I$ is the DC output current of the PV array.

For any arbitrary value of $G$ and $T_c$, the photocurrent, $I_{ph}$, is given by:

$$I_{ph} = \frac{G}{G^*}I_{scc} + k_i\left(T_c - T_c^*\right) \tag{4}$$

where $G^*$ and $T_c^*$ are respectively the irradiance and cell temperature at standard test conditions (STC): 1000 W/m$^2$ (AM1.5) and 25 °C, $k_i$ is the temperature coefficient of the current and $I_{scc}$ is the solar cell short circuit current at STC.

Each one of the strings of the PV array is formed by $Ns$ solar cells connected in series. The shunt current, $I_{sh}$, included in Eq. (2) can be calculated from:

$$I_{sh} = \frac{\frac{V}{N_s}+\frac{I\,R_s}{N_p}}{R_{sh}} \tag{5}$$

where $V$ is the Therefore DC output voltage of the PV array.

The diode current, $I_d$, included in Eq (2) is given by:

$$I_d = I_o\left[e^{\left(\frac{\frac{V}{N_s}+\frac{IR_s}{N_p}}{n\ V_t}\right)}-1\right] \tag{6}$$

where $I_o$ is the saturation current of the diode.

The saturation current of the diode presents a strong dependence on temperature and it is usually given by: