Contribution to the modeling of ageing effects in PV cells and modules

Bechara Nehme, Nkm Sirdi, Tilda Akiki, Aziz Naamane

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2014) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

6th International Conference on Sustainability in Energy and Buildings, SEB-14

Contribution to the modeling of ageing effects in PV cells and modules

Bechara Nehme[ab]*, Nacer K. M'Sirdi[a], Tilda Akiki[b], Aziz Naamane[a]

[a]Aix Marseille Université, CNRS, ENSAM, Université de Toulon, LSIS UMR 7296, 13397, Marseille France
[b]Département de Génie Électrique et Électronique, Faculté d'Ingénierie, Université Saint-Esprit de Kaslik, B.P. 446 Jounieh, Mont Liban – Liban

Abstract

In this paper, we present an overview of three degradation modes: the Potential Induced Degradation, the Light Induced Degradation, and the Ultraviolet Light Degradation. Then we develop a mathematical model that describes the latter degradation modes in order to evaluate the lifetime of PV (photovoltaic) modules. At the end we simulate the efficiency of a PV module as a function of time where the three degradation modes are taken into consideration.

Keywords: Degradation; PV panels; Potential Induced Degradation; Light Induced Degradation; Ultraviolet Degradation.

1. Introduction

The installed power of PV panels has reached 100 GWp; PV Panels are being installed from years and some of them have reached their end of life and must be replaced. We are focusing on increasing the lifetime of PV Panels. In fact, many causes defend our objective. First, with a relative low PV panel lifetime, the price of the produced KWh will increase and discourage the adoption of renewable energy sources in the market. Second, PV panels contain harmful materials like Cd (Cadmium) and Pb (Lead) that are classified as cancer causing agents. Third, the fabrication of PV panels needs rare raw materials as silver, indium, gallium and germanium. The availability of these latter materials influences the price of PV panels.

When talking about sustainability in energy we mean energy solutions that last for a long time. From this criterion we are trying to increase the lifetime of PV panels for more than 25 years. Many researchers from all over the world are studying the degradation of PV panels under stress. In previous studies,

* Bechara Nehme. Tel.:+961 9 600 960.
E-mail address: becharanehme@usek.edu.lb.

researchers described the degradation modes of PV panels. R. Swanson and al. explained the **PID (Potential induced degradation)** of PV panels; they showed how the system voltage affects PID [1]. Peter Hacke and al. showed the temperature effect on PID [2]. J Berghold and al. showed the effect of relative humidity on PID [3]. Bhushan Sopori and al. explained **LID (Light Induced Degradation)** in c-Si cells [4]. A. Herguth and al. showed the effect of temperature on LID and defined new states of the Boron-Oxygen complex that is responsible of LID in c-Si cells [5]. A. Kolodziej explained the LID in a-Si solar cells which is called SWE (Staebler-Wronski Effect). Kolodziej also showed the effect of illumination intensity on SWE [6]. F. J. Pern explained **UVD (Ultraviolet light Degradation)**, he showed the degradation over time [7]. Jae-Seong Jeong and al. showed the effect of temperature on UVD [8]. F. J. Pern and al. showed the effect of UVD on the mathematical model of a PV cell [9]. Other researchers explain mechanical impact on PV modules, others study temperature effect, interconnect degradation between cells or cell cracks.

In the latter literature researchers explained and described degradation modes. However few have presented a PV panel model that takes into consideration of its degradation in function of time. In this paper we try to build a mathematical model that gives the efficiency of a PV module as a function of its lifetime. The PID, LID, and UVD degradation modes will be modeled and their effect on the equivalent circuit of the PV cell will be taken into consideration.

In this paper we start by reviewing the PID, LID, and UVD degradation modes. Then we model the degradations as a function of parameters that affect their intensity. An empiric method is used taking data from literature experiences and using Matlab/Simulink/Simscape to evaluate the function parameters. At the end, a complete model is built that simulates the efficiency over the lifetime of the module.

Nomenclature

I	Output current of a cell in A
I_{SC}	Photo generated current of a cell in A
I_{01}	Saturation current of diode D1 in A
I_{010}	Saturation current of diode D1 before degradation in A
I_{02}	Saturation current of diode D2 in A
e	Electron charge $1.6x10^{-19}$C
k	Boltzmann constant $1.3806x10^{-23}$ $J.K^{-1}$
T	Temperature in K
V	Output voltage of the cell in V
R_s	Series resistor in Ω
R_{sh}	Shunt resistor in Ω
$I_{leakage}$	Leakage current in A
V_{op}	Operating voltage of the module with reference to ground in V
RH	Relative humidity
R	Gas constant 8.314 $J.mol^{-1}.K^{-1}$
t	Time in hours
Ir	Irradiance in $W.m^{-2}$
DYI	Change in yellowness index

2. Development of the mathematical model

In this section, we present the mathematical model of a normal PV cell. Then we review each degradation mode and describe how it will affect the PV cell model as a function of extrinsic and intrinsic parameters.

2.1. Mathematical model of a PV cell

A PV cell can be represented like a current source; its electrical model is described as a current source (I_{SC}) in parallel with two diodes (D1 and D2) and a shunt resistor (Rsh). The latter model is mounted in series with a resistor (Rs). The current generated I_{SC} is proportional to the incident irradiance G in $W.m^{-2}$ and to the temperature T in K. the current flowing in the shunt resistor (Rsh) represents the leakage current in the edge of the cell. The resistor Rs represents the internal losses of the PV cell caused by the electric contact [10]. The current I flowing in the load will become [11]:

$$I = I_{SC} - I_{01}\left(\exp\left(\frac{e(V+IR_s)}{KT}\right)-1\right) - \mathrm{I}_{02}\left(\exp\left(\frac{e(V+IR_s)}{2KT}\right)-1\right) - \frac{(\mathrm{V}+\mathrm{IR}_s)}{R_{sh}} \quad (1)$$

$I_{01}\left(\exp\left(\frac{eV+RI_s}{KT}\right)-1\right)$ corresponds to the current leaking in the first diode, it represents the recombination occurring in the neutral region. $\mathrm{I}_{02}\left(\exp\left(\frac{eV+RI_s}{2KT}\right)-1\right)$ corresponds to the current leaking in the second diode, it represents the recombination occurring in the depletion region.

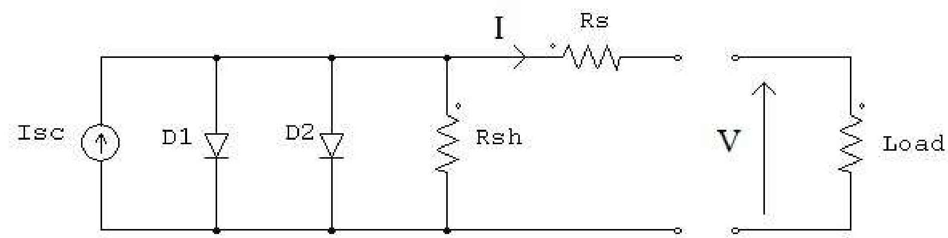

Figure 1. Equivalent circuit of a PV cell.

2.2. Potential Induced Degradation

PID increases the leakage current of a PV panel. The leakage current is defined to be the current that passes from the base to the emitter without traversing the load. The leakage current can be divided into four currents [11]. A current leaks through the soda-lime glass and through water molecules present on the surface (I1). A current leaks through electrons or ions present at the top surface of the cell (I2). A current leaks through the **EVA (Ethylene Vinyl Acetate)** encapsulation layer (I3). Finally, a current leaks in the back contact and closes the circuit (I4).

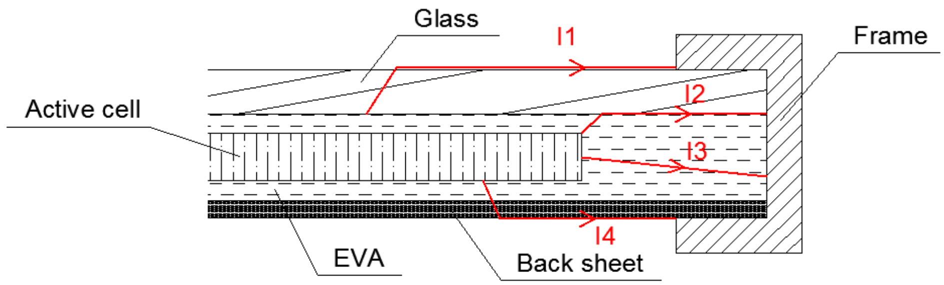

Figure 2. Cross section of a PV panel showing leakage current.

2.2.1 PID causes

Many causes lead to PID, they are divided into cell factors, module factors, system factors and environment factors. The cell factors are: the **ARC (Anti Reflective Coating)**, the emitter depth, and the base doping. Sodium ions present in the glass and in the ARC diffuse due to applied voltage into the front surface of the emitter. The sodium ions induce an electric field and cancel the passivation effect. This leads to an increased surface recombination current. Sodium may also diffuse into the n-doped emitter and acts as an electron acceptor and neutralize the n-doping. Tests showed that cells without ARC (SiNx Layer) are not subject to PID [12]. Other tests prove that high resistivity (low doping rate) of the base increases immunity to PID [3]. The module factors are related to the resistivity and isolation of the encapsulation. Degradation of EVA and of the soda-lime glass results in a decrease of the module encapsulation resistivity. The system factor that affects PID is called surface polarization effect. All frames are grounded and the active cell is polarized. An array is made of series and parallel modules. The potential difference between the cell and the frame increases with the module position in the string. The voltage can reach 600V in US standards or 1500V in European standards. This high voltage will lead to accumulation of electrons on the front surface of the cell leading to an increased surface recombination current and leakage current. The environment factors are mainly the humidity and the temperature. In fact, water molecules at the surface of the module increase the conductivity between the cell front surface and the frame. The temperature also increases the conductivity of the EVA and the encapsulation.

To mitigate or to reverse the PID effect, we can invert the polarization of the module in correspondence to the ground. In this case, the high electric voltage between the cell and the frame will be inverted reversing mobile charges (ions and electrons) diffusion. The cell surface will be clean thus decreasing the leakage current.

PV panels' installation can avoid PID. In a string of PV panels, the frames are grounded and one side of the active panels is grounded. If the positive side is grounded, the cells operate at negative voltage with respect to the frame. If the negative side is grounded, the cells operate at positive voltage with respect to the frame. In order to avoid PID, n-type front surface panels must be grounded from the positive side and p-type front surface panels must be grounded from the negative side. However, with new transformless inverters, the active panels must not be grounded to avoid ground fault current. In fact, the DC and the AC compartments are not isolated. In this case, the system operates at floating potential.

2.2.2 PID modeling

As explained before, the PID effect on PV panels relies on increasing the leakage current. We started to observe experiments and tests done by researchers to study the effect of each parameter on PID. We noticed that:

- The leakage current is proportional to the square of the panel to ground voltage [1]
- The leakage current is proportional to the square of the relative humidity [3]
- The leakage current follows an Arrhenius equation with an activation energy of 0.94 eV [2]
- The leakage current is proportional to the square of the panel lifetime [3]

Starting from literature experiments that were made under several conditions, we managed to fit the experimental results and obtained the model using matlab/simulink/simscape software. The PID effect on PV panels is described by the following equation:

$$I_{leakage} = 1.5\times10^{-17}\times Vop^2\times RH^2\times\exp\left(\frac{-90700}{R\times T}\right)\times(1\times10^{-8}\times \mathrm{t})^2 \qquad (2)$$

The coefficient 1.5×10^{-17} may vary because the dependence of the cell factors. In fact, the leakage current depends also on the resistivity of the base.

2.3. Light Induced Degradation

LID increases the recombination current in the base. LID occurs to n-type emitter crystalline silicon cells and to amorphous silicon cells. It affects c-Si cells for about 3% and affects a-Si cells for about 30%.

2.3.1 LID in c-Si cells

In n-type emitter crystalline silicon cells, the base is doped with boron which is an acceptor. During Czochralski manufacturing process, oxygen atoms diffuse into silicon. When exposed to light, boron loses the hole and attracts the oxygen atom. A B-O complex is formed that forms a trap to electron and holes; thus increasing the recombination current. LID is proportional to the concentration of oxygen and boron in the base. Oxygen is present due to quartz crucible melting during hot silicon processing at 1412ºC. The concentration of oxygen is about $5\text{x}10^{17}$ to $1\text{x}10^{18}$ cm^{-3}. The concentration of boron affects the base resistivity and the total efficiency of the cell. That is why a tradeoff must be adopted and a base resistivity of 3-6 Ωcm is used [5]. The degradation takes about 72 hours of illumination.

One of several actions may be undertaken to recover from LID. First we may apply a forward bias current; this phenomenon is called “Current Induced Regeneration”. Or we may anneal the bulk at a temperature of 200 ºC [4]. Or we can wait for the B-O complex to regenerate with time under light [5]. To understand this mechanism, we define three states of the B-O complex. State 1 of the complex represents no activity toward electron hole recombination, this is the annealed state. State 2 of the complex represents high activity toward electron hole recombination, this is the degraded state. State 3 of the complex represents low activity toward electron hole recombination; this is the regenerated state [5]. The B-O complex can degrade under light from state 1 to state 2. The degradation follows an Arrhenius equation with an activation energy of 0.45 eV. The B-O complex can anneal from state 2 to state 1 under 200ºC for 30 min [4]. The B-O complex can regenerate from state 2 to state 3 under light soaking. The regeneration follows an Arrhenius equation with an activation energy of 1.4 eV. It is proved by experiments that the regenerated state (state 3) is stable at solar cell operating conditions; however the annealed state (state 1) is unstable.

2.3.2 LID modeling in c-Si cells

As explained before, the LID effect on PV panels relies on increasing the recombination current I_{01}. We started to observe experiments and tests done by researchers to study the effect of each parameter on LID. We noticed that:

- The recombination current change is proportional to the irradiance
- The recombination current change follows an Arrhenius equation with an activation energy of 0.45eV [5]
- The recombination current change is proportional to the illumination time [5]

Fitting the experimental results that were made for different temperatures and using matlab/simulink/simscape software we managed to model the LID effect on c-Si PV panels:

$$I_{01} = I_{010} + 1.1 \times 10^{-23} \times (\frac{Ir}{1000}) \times \exp(\frac{-43268}{R \times T}) \times \mathrm{t} \tag{3}$$

The coefficient 1.1×10^{-23} may vary because of the dependence of the recombination current on the boron concentration and on the dimensions of the cell.

2.3.3 LID in a-Si cells

LID that occurs to amorphous silicon cells is called SWE (Staebler-Wronski Effect). It was discovered by Staebler and Wronski in 1977. The excessive light soaking increases the dandling bonds which increase the recombination rate. This effect is noted in multi-junction micromorph solar cells. These cells are built by a µc-Si cell in the bottom and an a-Si:H cell in the top. This structure is used because a-Si:H cell absorbs high energy photons.

Two possible ways exist for recovering from the SWE. The first is by annealing the bulk at a 160 ºC for a few minutes [1]. And the other is by applying a bias voltage under illumination for 30 min. The above mentioned information proves the increase in efficiency of a-Si:H cells with high temperature. The bias voltage and the photo-generated electron will allow the reformation of the Si-H bond, which will recover the initial status of the cell.

2.3.4 LID modeling in a-Si cells

As explained before, the LID effect on PV panels relies on increasing the recombination current I_{01}. We started to observe experiments and tests done by researchers to study the effect of each parameter on LID. We noticed that:

- The density of dandling bonds is proportional to the irradiance to the power of 2/3 [6]
- The density of dandling bonds is proportional to the illumination time to the power of 1/3 [6]
- The density of dandling bonds saturates at a level of 5×10^{16} cm^{-3} [6]

- The recombination current is proportional to the logarithm of the density of dandling bonds
- The temperature does not affect the LID in a-Si solar cells [6]

Fitting the experimental results and using matlab/simulink/simscape software we managed to model the LID effect on a-Si PV panels:

$$I_{01} = I_{010} + 1.9\times10^{-6} \times \log(1\times10^{-2} \times \mathrm{Ir}^{2/3} \times \mathrm{t}^{1/3}) \tag{4}$$

The coefficient 1.9×10^{-6} may vary because of the dependence of the recombination current on the dimensions of the cell.

2.4. Ultraviolet light Degradation

UV (Ultraviolet) lights are electromagnetic radiations with a low wavelength (10nm-400nm). They carry high energy and are partially present in the terrestrial solar spectrum. Si represents low SR (Spectral Response) towards UV light and UV light is harmful to PV panels. In fact, PV panels are subject to yellowing after some years of operating under sun light. Precisely, the EVA encapsulation degrades under UV illumination and become light yellow, then yellow-brown, and dark brown. The latter is called EVA discoloration.

2.4.1 UV Degradation mechanism

The encapsulation is used for optical coupling, electrical isolation, physical isolation protection, mechanical support, and thermal conduction for the PV panel. The EVA is constituted of 70% of gel content and 0.3 wt% (weight percentage) of Cyasorb UV 531. Cyasorb UV 531 absorbs UV light between 240 and 340nm. Its melting point is 49 ºC. EVA degradation is calculated upon gel and Cyasorb UV 531 content. In fact, after UV light illumination, the gel content increases and the Cyasorb UV 531 content decreases. The latter is no more found in dark brown EVA. Acetic acid and volatile organic components are also produced by UV light exposure [9].

The effect of EVA discoloration on PV modules resides in the decrease of the EVA transmittance. In fact, with time the transmittance of the EVA encapsulation decreases for high energy photons; which reduces the PV panel efficiency.

2.4.2 UV degradation modeling

The UV light affects the EVA encapsulation. However, in modeling we found out that the series resistor R_s and the shunt resistor R_{sh} are varied [9]. We use the YI (Yellowness Index) to describe the encapsulation discoloration. The variation DYI (Delta YI) is observed with time. R_s and R_{sh} are then calculated as a function to the DYI. We started to observe experiments and tests done by researchers to study the effect of each parameter on UVD. We noticed that:

- The DYI follows an Arrhenius equation with an activation energy of 0.93eV [8]
- The DYI is proportional to the irradiance intensity [7]
- The DYI is proportional to the logarithm of the illumination time [7]

Fitting the experimental results and using matlab/simulink/simscape software, we managed to model the UVD effect on PV panels:

$$DYI = 9.1\times10^{-24}\times\exp(\frac{-90000}{R\times T})\times \mathrm{Ir}\times\log(\mathrm{t}) \quad (5)$$

$$R_{sh} = R_{sh0} - 193\times DYI \quad (6)$$

$$R_{s} = R_{s0} + 9.9\times10^{-3}\times DYI \quad (7)$$

3. Simulation of module efficiency with time

In this part we will explore our model. We simulate the effect of the three combined degradation modes on the efficiency of a PV module. The model is developed under matlab/simulink/simscape. A c-Si PV panel is taken into consideration. It is built with two strings of 12 cells each. Each cell delivers 5.5A under standard test conditions. Simulations for a-Si PV panels are not included in this paper because of number of pages limitation. The results will be presented during the conference.

The illumination and the temperature are made variable during the day and during the year. The operating voltage V_{op}, the relative humidity RH, the maximum irradiance (at noon) Ir, and the maximum temperature (at noon) T are variables that can be entered by user. For simplicity reasons, and because PID and UVD are slow mechanisms, the temperature and the illumination are taken constant across the years. However, for LID which affects the cell for the first days of exposure, degradation is made dependent of illumination and temperature with variation during the day and during the year.

The first simulation shows the normalized efficiency over the lifetime of the module. For the first 300 hours of operation, the efficiency is calculated each 25 hours. Then the efficiency is calculated each 300 hours. The normalized efficiency is given by dividing the power in **STC (Standard Test Conditions)** over the initial power in the same conditions for the first hour. In our simulation, the model operates at V_{op}=80V, the environment is characterised by a relative humidity RH=65%.

For each hour the calculation is made as follows:

$$I_{01} = I_{010} + 1.1\times10^{-23}\times(\frac{Ir(\mathrm{t})}{1000})\times\exp(\frac{-43268}{R\times T(t)})\times \mathrm{t} \quad (3)$$

$$I_{leakage} = 1.5\times10^{-17}\times Vop^{2}\times RH^{2}\times\exp(\frac{-90700}{R\times T})\times(1\times10^{-8}\times \mathrm{t})^{2} \quad (2)$$

$$DYI = 9.1\times10^{-24}\times\exp(\frac{-90000}{R\times T})\times \mathrm{Ir}\times\log(\mathrm{t}) \quad (5)$$

$$R_{sh} = R_{sh0} - 193\times DYI \quad (6)$$

$$R_{s} = R_{s0} + 9.9\times10^{-3}\times DYI \quad (7)$$

$$NormalizedEfficiency(t) = \frac{P_{STC}(t)}{P_{STC}(0)} \quad (8)$$

The saturation current of the diode D1, the shunt resistor, and the series resistor are updated and the model is simulated then the output power is noted. The latter is repeated for 36000 hours which correspond to 10 years of module operation.

For figure 3, the maximum illumination is fixed to Ir=1000 W.m^{-2}. The simulation is repeated for three maximum temperatures T=35^{o}C in blue, T=45 ^{o}C in red, and T=55 ^{o}C in purple. The effect of temperature is clearly shown; with temperature increase, the module efficiency decreases rapidly during all years.

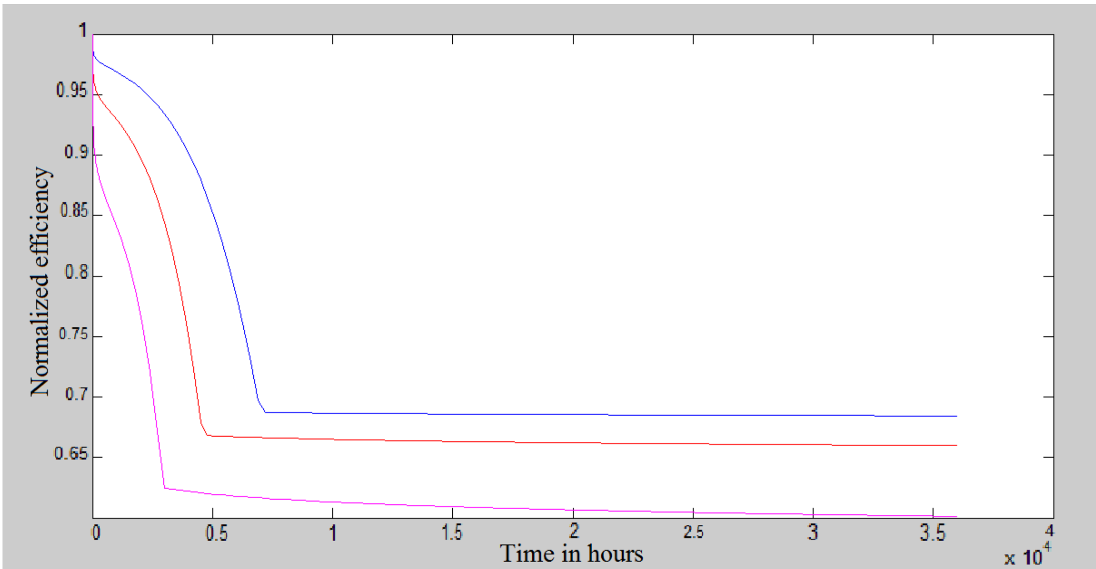

Figure 3. Normalized efficiency with variant maximum temperature.

For figure 4, the maximum temperature is fixed to T=45 ^{o}C. The simulation is repeated for three maximum illuminations Ir=700 W.m^{-2} in blue, Ir=1000 W.m^{-2} in red, and Ir=1200 W.m^{-2} in magenta. The effect of irradiance is clearly visible; with irradiance increase, the module efficiency decreases rapidly regarding the LID and the UVD.

Figures 3 and 4 respond well to the predefined equations. At first days, we find dramatic decrease of the efficiency caused by the LID which saturates after a while. Then we find a parabolic decrease of the efficiency which corresponds to the increase of the leakage current caused by PID. This current then saturates. After around 5000 hours of operation the UVD degradation remains affecting the module. The latter is compatible with field observation.

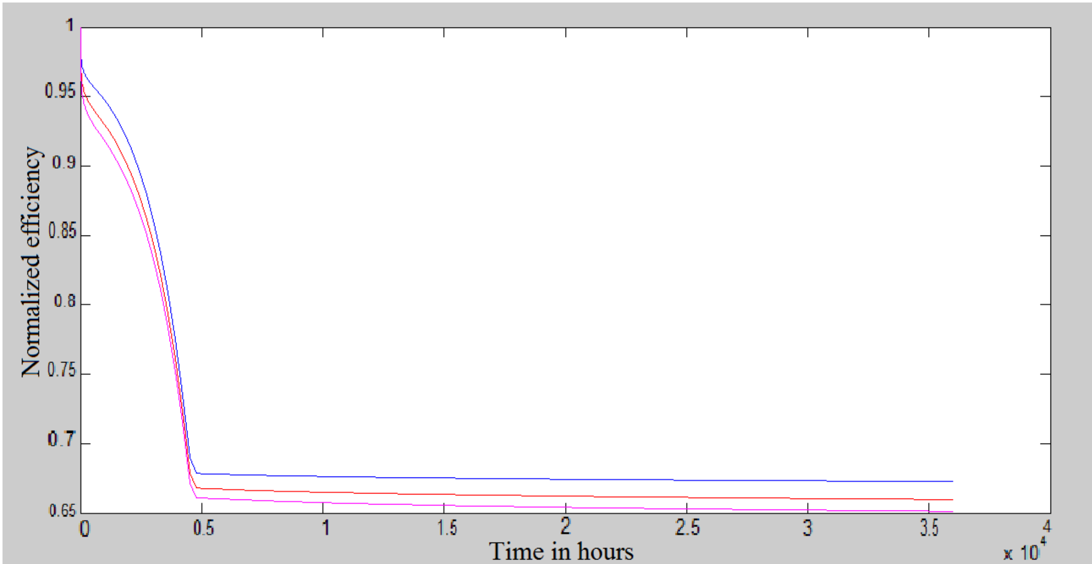

Figure 4. Normalized efficiency with variant maximum irradiance.

The second simulation shows the output power of the panel for its first 100 days of operation. In the figure, we represent only one day over ten. During ten days, we plot the first day only. The variations of the irradiance and of the temperature during the day and during the year are taken into consideration. In our simulation, the model operates at V_{op}=80V, the environment is characterised by a relative humidity RH=65%. The maximum irradiance is set to Ir=1000 W.m^{-2} and the maximum temperature is set to T=45 ^{o}C. For figure 5, in blue we see the output of the PV module without degradation, and in red we see its output with the combined effect of the three degradations. It is clearly shown that the power decreases with time.

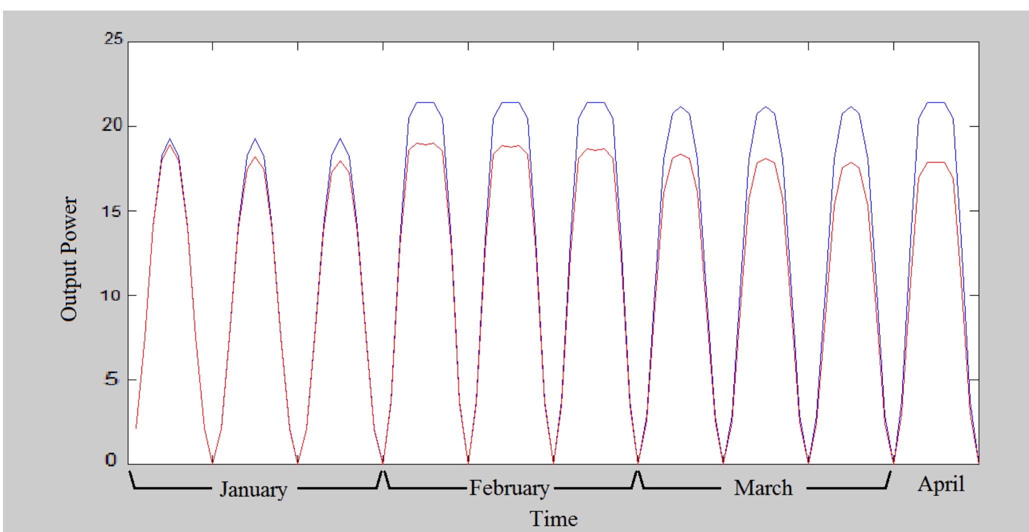

Figure 5. Output power of the non degraded (blue) and degraded (red) PV module.

4. Conclusion

Many researchers explained and described PV modules degradation modes separately. However few of them modelled these degradations. In order to increase the lifetime of PV modules, we started first to model all the degradation modes. In this paper, PID, LID, and UVD modes were reviewed and modelled using an empiric method based on existing literature. The obtained model, gathering all the degradations, was used to simulate the efficiency variation with time of a module constituted with two strings of 12 cells. This work must be continued to explore all degradation modes and our perspectives are to model their effect on PV modules and try to use a diagnosis to alleviate their effects.

References

[1] R. Swanson, M. Cudzinovic, D. DeCeuster, V. Desai , Jörn Jürgens , N. Kaminar, W. Mulligan, L. Rodrigues-Barbarosa, D. Rose, D. Smith, A. Terao, and K. Wilson. *The surface polarization effect in high-efficiency silicon solar cells*, 15th PVSEC, 2005.

[2] Hacke, P., Terwilliger, K., Smith, R., Glick, S., Pankow, J., Kempe, M., ... & Kloos, M. *System voltage potential-induced degradation mechanisms in PV modules and methods for test*, 37th IEEE PVSC 2011:000814-000820.

[3] Pingel, S., Frank, O., Winkler, M., Daryan, S., Geipel, T., Hoehne, H., & Berghold, J. *Potential Induced Degradation of solar cells and* panels, 35th IEEE PVSC 2010:002817-002822.

[4] Sopori, B., Basnyat, P., Devayajanam, S., Shet, S., Mehta, V., Binns, J., & Appel, J. *Understanding light-induced degradation of c-Si solar cell,* 38th IEEE PVSC 2012:001115-001120.

[5] A. Herguth, G. Schubert, M. Kaes and G. Hahn. *Avoiding boron-oxygen related degradation in highly boron doped CZ silicon,* 21rt EU-PVSEC 2006.

[6] Kołodziej, A. *Staebler-Wronski effect in amorphous silicon and its alloy,* Opto-electronics review,2004, 12, 21-32.

[7] Pern, F. J. *Factors that affect the EVA encapsulant discoloration rate upon accelerated exposur,* Solar energy materials and solar cells, 1996, 41, 587-615.

[8] Jae-Seong Jeong, Nochang Park. *Field Discoloration Analysis and UV/temperature Accelerated Degradation Test of EVA for PV,* 2013, IEEE, 978-1-4799-3299.

[9] Pern, F. J., Czanderna, A. W., Emery, K. A., & Dhere, R. G. *Weathering degradation of EVA encapsulant and the effect of its yellowing on solar cell efficiency.* 22nd IEEE PVSC 1991,557-561.

[10] 1982. Basic Photovoltaic Principles and Methods

[11] Luque Antonio and Hegedus Steven, 2003. Handbook of Photovoltaic Science and Engineering, England: Wiley.

[12] Koch, S., Seidel, C., Grunow, P., Krauter, S., & Schoppa. *Polarization effects and tests for crystalline silicon cells,* 26th EU PVSEC, 2011, 17261731.