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# Assessing the Effect of Temperature on Degradation Modes of PV Panels

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**Abstract**— PV panels are affected by many degradation modes. We list the Potential Induced Degradation, the Light Induced Degradation, the UltraViolet Light Degradation, the Moisture Induced Degradation, and the Cell Cracks. These degradation modes are affected by external environmental conditions as irradiance, temperature and humidity. The common factor that affects the degradation modes is temperature. The degradation process follows an Arrhenius equation; it is exponentially related to temperature. In this paper we evaluate precisely the effect of temperature on the degradation process of PV panels.

**Keywords**— Temperature, Potential Induced Degradation, Light Induced Degradation, UltraViolet Degradation, Temperature, Efficiency, Mitigation

## I. INTRODUCTION

People are relying more on the PV (Photovoltaic) production of energy. This is why reliability and efficiency of this energy source are becoming a concern. From here we focus on decreasing the degradation process of PV panels. In addition, the manufacturing of PV panels is expensive and needs rare raw materials like Indium, Silver, Germanium, and Gallium, or contain cancer causing elements like Cadmium and Lead [1].

In literature, researchers conducted many experiments to examine the effects of environmental and operational conditions on degradation modes. R. Swanson and al. explained the Potential induced degradation (PID) of PV panels; they showed how the system voltage affects PID [2]. Peter Hacke and al. showed the temperature effect on PID [3]. J Berghold and al. showed the effect of relative humidity on PID [4]. Bhushan Sopori and al. explained Light Induced Degradation (LID) in c-Si cells [5]. 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 [6]. A. Kolodziej explained the LID in a-Si solar cells which is called StaeblerWronski Effect (SWE). Kolodziej also showed the

effect of illumination intensity on SWE [7]. F. J. Pern explained Ultraviolet light Degradation (UVD), he showed the degradation over time [8]. Jae-Seong Jeong and al. showed the effect of temperature on UVD [9]. F. J. Pern and al. showed the effect of UVD on the mathematical model of a PV cell [10]. Melissa A. Yaklin and al. showed the effect of humidity on TCO Transparent Conductive Oxide (TCO) [11]. Michael D. Kempe focused on the ingress of moisture into PV panels [12]. Jane Kapur and al. showed the geometrical repartition of moisture in the PV panel [13]. Sarah Kajari-Schröder and al. showed the geometrical and directional repartition of cracks in a PV panel [14]. S. KajariSchröder and al. explained when cracks become critical to PV cell [15]. M. Köntges and al. simulated the effect of cracks on power production [16]. In our previous works we modeled all degradations as function of time and of external environmental conditions [17], [18]. We also enhanced our model for taking into consideration the fact that external conditions vary during the day and during the year [19].

In this paper we assess the effect of temperature on degradation process. First we recall the equivalent circuit of a PV cell. Then we recall the degradation equations. This shows the main importance of our model to describe the systems behavior and aging.

## II. EQUIVALENT CIRCUIT OF A PV CELL

The equivalent circuit of a PV cell is a current source ( $I_{SC}$ ) mounted in parallel with two diodes ( $D_1$  and  $D_2$ ) and a shunt resistor ( $R_{sh}$ ). A series resistor ( $R_s$ ) is added to complete the model. The current generated  $I_{SC}$  is proportional to the incident irradiance  $G$  in  $W.m^{-2}$  and increases with temperature  $T$  in K. The current flowing in the shunt resistor ( $R_{sh}$ ) represents the leakage current in the edge of the cell. The resistor  $R_s$  models the electric contact resistance. The current  $I$  (in A) delivered to the load will become [1]:

$$I = I_{sc} - I_{01} \left( \exp \left( \frac{e(V + I \times R_s)}{K \times T} \right) - 1 \right) - I_{02} \left( \exp \left( \frac{e(V + I \times R_s)}{2 \times K \times T} \right) - 1 \right) - \frac{(V + I \times R_s)}{R_{sh}}$$

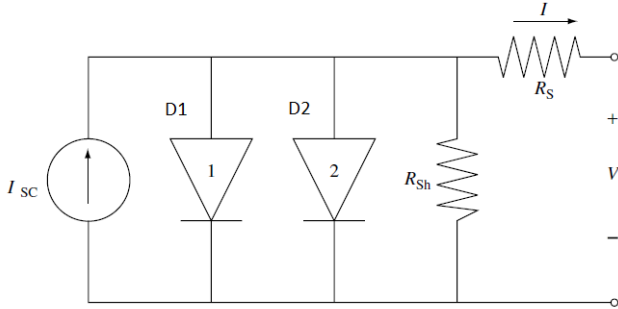


Figure 1 Equivalent Circuit of a PV cell.

Where:

- $I_{01}$  is the saturation current of diode  $D_1$  in A
- $I_{02}$  is the saturation current of the diode  $D_2$  in A
- $e$  is the electron charge  $1.6 \times 10^{-19} \text{C}$
- $V$  is the output voltage of the cell in V
- $K$  is the Boltzmann constant  $1.3806 \times 10^{-23} \text{ J.K}^{-1}$
- $T$  is the temperature in K.

### III. MODELING DEGRADATION MODES

When a PV cell is subject to degradation, its equivalent circuit is modified. In fact, the elements of the equivalent circuit will vary [17-18]. Qualitatively, The  $I_{sc}$  and the  $R_{sh}$  will decrease, The  $I_{01}$ , the  $I_{02}$ , and the  $R_s$  will increase.

#### A. PID Modeling

PID increases the leakage current of a PV panel, it is modeled by a decrease in  $R_{sh}$ . It is explained by high difference in voltage between the active cell part and the edge of the panel. The voltage will cause electrons to move and to set a path between the N doped and P doped parts of the cell. It is also affected by relative humidity and follows an Arrhenius equation with an activation energy of 0.94 eV [2-4]. The Arrhenius equation is described as following:

$$A = K \times \left( \frac{-E_a}{R \times T} \right)$$

Where:

- $K$  is the constant rate
- $E_a$  activation energy in eV
- $R$  gas constant  $8.314 \text{ J.mol}^{-1}.\text{K}^{-1}$

#### B. LID Modeling

LID increases  $I_{01}$  and  $I_{02}$ . In reality, the recombination current is increased in the base of the cell. LID occurs to n-type emitter crystalline silicon cells and to amorphous silicon cells. In amorphous silicon cells it is known as the SWE. LID is manly

affected by the intensity of illumination and follows an Arrhenius equation with an activation energy of 0.45 eV [5-7].

#### C. UVD Modeling

The UV light affects the EVA encapsulation. Apparently the transmittance of the encapsulation will be affected. However, in modeling the  $R_s$  and  $R_{sh}$  resistors are affected by the discoloration of the EVA encapsulation. The latter is measured by a factor denoted Delta Yellowness Index (DYI) [8-10, 17]. The  $R_s$  will increase and the  $R_{sh}$  will decrease.

#### D. MID Modeling

The ingress of moisture in the panel affects the Transparent Conductive Oxide (TCO) layer which is used with thin film technologies. The TCO resistance increases as an effect of humidity. However, not all cells are affected alike due to unequal repartition of moisture in the panel. Water is more likely to be near the edges of the panel than at the center of the panel. The moisture repartition in the panel follows a sine equation. The water ingress in the panel follows an Arrhenius equation with an activation energy of 0.38 eV. And the degradation of TCO layer follows an Arrhenius equation with an activation energy of 0.91 eV [11-13].

#### E. Cell Cracks

Cell cracks happen manly due to snow accumulation on panels. The criticality of a crack depends on its orientation and if it has encountered freeze cycles. The cell cracks reduce the active cell area. Thus it decreases the short circuit current ( $I_{sc}$ ) and the recombination currents ( $I_{01}$  and  $I_{02}$ ) [14-16].

TABLE 1 SUMMARY TABLE OF ALL DEGRADATION MODES AND THEIR FACTORS.

Factors	PID	LID	UVD	MID	Cell Cracks
Temperature	$R_{sh}$ Decr	$I_{01}$ Incr $I_{02}$ Incr	$R_s$ Incr $R_{sh}$ Decr	$R_s$ Incr	-
Humidity	$R_{sh}$ Decr	-	-	$R_s$ Incr	-
Irradiance	-	$I_{01}$ Incr $I_{02}$ Incr	$R_s$ Incr $R_{sh}$ Decr	-	-
Snow, freeze	-	-	-	-	$I_{sc}$ Decr $I_{01}$ Decr $I_{02}$ Decr

### IV. MODELING DEGRADATION MODES

In this section we give the degradation equations. These equations describe the elements of the equivalent circuit according to external environmental conditions, operation, and events. The short circuit current is given by the following formula:

$$I_{sc,deg} = I_{sc,T1,ref} \times \left( 1 - \frac{A_{inactive}}{A_{total}} \right)$$

Where:

- $I_{sc,T1,ref}$  is The Short Circuit current in Standard Test Conditions (STC) conditions in A
- $A_{inactive}$  is The inactive cell area in  $\text{cm}^2$
- $A_{total}$  is The total cell area in  $\text{cm}^2$

As a function of time the value of the saturation current of diode  $D_1$  of a degraded cell is expressed by:

$$I_{01,deg} = \left( I_{01,T1ref} + 1.11 \times 10^{-10} \times \frac{G}{1000} \times \exp\left(\frac{-43268}{R \times T}\right) \times t \right) \times \left( 1 - \frac{A_{inactive}}{A_{total}} \right)$$

Where:

$I_{01,T1,ref}$  is the saturation current of diode  $D_1$  in STC in A

$G$  is the actual irradiance in  $W.m^{-2}$

$R$  is the Gas constant  $8.314 J.mol^{-1}.K^{-1}$

$t$  is Time in s.

The same calculation is made to the saturation current of diode  $D_2$ ,  $I_{02,deg}$  with an ideality factor of 2.

The DYI is given by:

$$DYI = 5.68 \times 10^{11} \times \exp\left(\frac{-90000}{R \times T_{avg}}\right) \times G_{avg} \times \log\left(\frac{t}{3600}\right)$$

Where:

$T_{avg}$  is the average temperature in K

$G_{avg}$  average Irradiance in  $W.m^{-2}$

As a function of time the value of the series resistor  $R_{s,deg}$  of a degraded cell is expressed by:

$$R_s = (R_{s,T1ref} + 9.9 \times 10^{-3} \times DYI)$$

Where,  $R_{s,T1,ref}$  is the series resistance in STC in  $\Omega$

As a function of time the value of the shunt resistor  $R_{sh,deg}$  of a degraded cell is expressed by:

$$R_{sh,deg} = \frac{(R_{sh,T1ref} - 193 \times DYI)}{\left( 7 \times 10^{-6} \times V_{op}^2 \times RH^2 \times \exp\left(\frac{-90700}{R \times T_{avg}}\right) \times t^2 \right) (R_{sh,T1ref} - 193 \times DYI) + 1}$$

Where:

$R_{sh,T1,ref}$  is the shunt resistance in  $\Omega$

$V_{op}$  is the Operation voltage of the panel in V

$RH$  is the Relative humidity

We can see clearly in the above equations that temperature affects the elements of the equivalent circuit of PV panels by an exponential factor. The actual temperature also affects any resistor by increasing its value. We can see that all degradation modes are temperature and time dependent. From here we must evaluate the power generated by a panel in order to assess the effect of temperature on the efficiency of the panel. Thus, we will use our developed model to simulate the power produced by a Panel over time with different temperatures.

## V. SIMULATION RESULTS

The simulation is done for 10 years. Over the 10 years the panel operates at the MPP (Maximum Power Point). The average relative humidity of the location is 50%. The maximum irradiance (summer, noon) of the location is  $1000 W.m^{-2}$ . And the operation voltage is 50V. We know that the model takes into consideration the variation of the relative humidity, the irradiance, and the temperature during the day and during the year.

In order to assess quantitatively the temperature effect on the degradation process of PV panel, it was varied first from 45°C to

49°C and the simulation results are presented in figure 2. In figure 3 we varied the temperature from 35°C to 39°C. In figure 4 we varied the temperature from 25°C to 29°C.

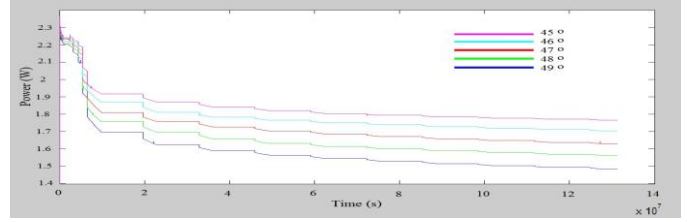


Figure 2 Power Output for a variation in temperature from 45°C to 49°C

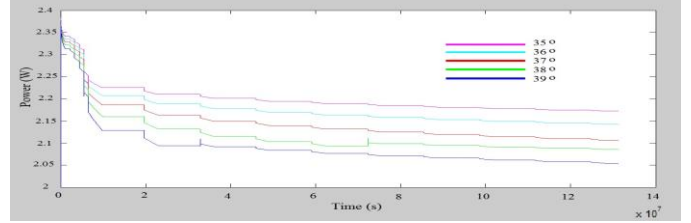


Figure 3 Power output for a variation in temperature from 35°C to 39°C.

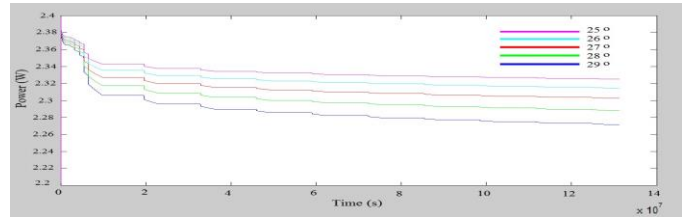


Figure 4 Power output for a variation in temperature from 25°C to 29°C.

## VI. DISCUSSION

We can see clearly that with high temperature high degradation process occurs. In fact, the degradation is exponentially linked to the temperature value. We can see also that the most power loss occurs in the first two years.

Now let's assess the reduction of temperature. Calculating the mean percentage of power loss reduction when decreasing the temperature of 1°C for high temperatures (45°C to 49°C) we get:  $R=0,025=2,5\%$ . This mean for each degree of reduction the degradation process will be mitigated by 2.5%. The same calculation is made for the range of middle temperature (35°C to 39°C) we find  $R=0,0094=0,94\%$ . And for the low temperature range (25°C to 29°C) we find  $R=0,0065=0,65\%$ . Analyzing these results gives us an image on the reduction effect of temperature on degradation. We can see that a reduction in 1°C when operating at high temperature mitigates the degradation by 2.5%. However, a reduction of 1°C in middle and low temperature ranges only mitigates the degradation by 0.94% and 0.65% respectively. This leads to focusing on reducing the temperature during high ranges times. In details, for a 47°C the panel loses 30.65% of its initial efficiency. If we decrease the temperature by 1°C, for 46°C the panel loses 27.63% of its initial efficiency. However, when working on low temperature ranges, the panel loses 2.4% and 1.95% for 27°C and 26°C respectively. For 1°C of temperature reduction, the mitigation of degradation is more important for higher temperatures.

## VII. CONCLUSION

In previous works we have built a precise model of PV panel degradation modes. Degradation is affected by external conditions like temperature, humidity, irradiance and by operational conditions. In this paper, we assess the effect of temperature on degradation mechanism. We found that a reduction in temperature of 1°C reduces the degradation process unequally when operating in high or low temperature ranges. From here emerges a recommendation for future works that any attempt to temperature reduction must be enrolled in high temperature ranges.

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