

Effect of a Thermal Nonlinear Absorption Coefficient on the Dynamics of a Photovoltaic Panel

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Abstract

In this article, we propose a theoretical study of the effect of a thermal nonlinear absorption coefficient on the dynamics of a photovoltaic (PV) panel. This coefficient is expressed as a quadratic function of temperature of a PV module known as active zone of a PV panel. Based on the energy balance at each layer of a PV panel, the mathematical expressions of the temperature on each layer are derived. A comparative study of the thermal behavior of a PV panel for a constant and nonlinear coefficient is made, thanks to the numerical investigations carried out in the MATLAB environment. We reveal that, this nonlinear absorption coefficient induces the cooling of a PV panel as a whole, and optimize the electrical efficiency of a PV panel around 2.5%.

Keywords: Nonlinear absorption coefficient, recombination process, electrical efficiency, diffusion process, PV panel.

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1. Introduction

Energy production today, is a huge challenge. Indeed, as the energy needs of industrialized countries increase exponentially over time, they need more energy to develop their countries. Today, most of the world's energy production is provided by fossil fuels and nuclear known as non renewable source of energy. The consumption of these non renewable sources of energy, impacts on the environment by spoiling the fauna, flora and the climatic changes. To face this issue of pollution, the development of new cleaning non-polluting sources of energy must be explored. Fortunately, thanks to the renewable energies, our expectations can be met (Rahul *et al.*, 2014). This type of energy has revolutionized the energy sector worldwide. It can be subdivided into several branches such as solar energy, wind, geothermal energy just to name a few (Nottom *et al.*, 1996). The above-mentioned energies come mainly from solar energy (Sanjeev *et al.*, 2016) which is a second form of energy used by human being after the muscular energy. In addition, the energy coming from the sun is very important and presents a solar potential of about 1340W/m². This potential can be directly transformed into electricity thanks to the PV cells and into thermal energy through the solar collector depending of needing. However, in the view of solving the need of electrical energy in isolated area, people used more than more PV panels based on photovoltaic conversion. Since the pioneering work of Becquerel (1939) showing that photovoltaic effect results from the interaction between a photon (quantum of light) and the matter (electron) which produces current and electric voltage, this concept has been intensively studied. Latter Einstein (1917) explained the photovoltaic effect using the basic principle of quantum mechanics. Depending on the current or voltage sought, solar cells can be grouped in series, parallel, and compound to form a PV module (Emmanuel, 2006). Despite the conversion of the solar radiation into electricity thank to a PV cell, its electrical efficiency is still very low due to the factors that affect negatively its dynamics. It is the reason why since the past decades many researches are continued to be done aiming to optimize its electrical performances and maintain it in operating temperature. This can be explained by many research works. Indeed, Siyu *et al.* (2016) studied the local effects of inhomogeneity of a silicon solar cell. They showed that, the inhomogeneity causes the decrement of the open circuit voltage of a PV cell while the short circuit current increases. Osueke (2015) optimized the parameters of the solar cells through an experiment based on the angle of tilt, the angle of azimuth. He showed that the angle of tilt increases with the electrical efficiency. Following the same goal, Mohamed *et al.* (2008) conducted studies on an exponential model of a series resistance. Their work revealed that this profile of series resistance optimizes the electrical efficiency of a solar cell. Still in the line to improve the performances of a solar cell, Shahrin *et al.* (2011) established that the accumulation of dust on the surface of a solar cell causes the drop of its electrical parameters of about 50%. On the order hand, Garg *et al.* (1973) demonstrated that when a PV module is inclined under an angle of 45 degrees, its transmission coefficient and its performance both decrease. In 2010, Nottom *et al.* showed that when a PV module is shaded, its electrical performances decrease. Moreover, Mohammad *et al.* (2016) and Xu *et al.* (2014) established that, when a solar cell is exposed to the sun, about 9-12% of the solar radiation is converted into electricity. The rest is absorbed by the solar cell, leading to the growth of its operating temperature and therefore to the reduction of its electrical efficiency about 0.45% per degree Celsius (Davud *et al.*, 2013; Gao *et al.*, 2010; Kalogirou *et al.*, 2006; Latifa *et al.*, 2014; Skoplaki *et al.*, 2009). Furthermore, as the nature is essentially nonlinear, Dongo *et al.* (2014) worked on the effects of a thermal nonlinear series resistance, based on an electrical model of a solar cell. They showed

that the nonlinear character of the series resistance optimizes of about 3.6% the power of a PV cell. These previous mentioned works traduce the great desire to deeply master the dynamics of the PV cell in order to propose new approaches that assure their stabilities and improve their yield.

Highly motivated by the nonlinearity like Dongo *et al.* (2014) and the amount of energy dissipated in the PV module, we plan to study theoretically the effect of a nonlinear absorption coefficient of a PV module. This coefficient is expressed as a quadratic function of the temperature across it, in replacement of the constant absorption coefficient commonly used in the scientific literature. To achieve our goal, the structure of this paper is organized as follows. In section 2, we present the different parts of a PV panel which lead to the mathematical formulations thanks to the energy balance. In section 3, simulations of the mathematical expressions are made exploiting the MATLAB environment. Comparison and discussion of the results obtained are carried out in the cases of constant and nonlinear absorption coefficients of a solar cell, ended by discussions and concluding remarks.

2. Mathematical formulation

2.1. Description of a PV panel

A PV panel consists of several layers like glass, active zone known as PV module, Teldar and EVA as shown on figure 1. However, in practice the depth and heat capacities of Teldar and EVA are very small justifying why these layers are neglected in various studies. Therefore, the simplified PV panel is made of two layers as drawn on figure 2. On this figure, the first layer is the glass that physically protects the solar cell against the projectiles capable to destroy the PV panel. Known as the electronic part, the second layer is the PV module consisting of an association of identical solar cells in which the photogeneration, the diffusion and the recombination process of minority carriers take place.

Within our investigations, the sky is considered as a black body at constant temperature. It is also assumed that losses at the front and back surface of the PV panel are identical, and the effect of the dust at the front surface of the PV panel is negligible. We also consider that the temperature of each layer varies slowly with time. Then, the time derivative in the energy balance is neglected. We also admit that our searches are conducted in the steady state, and that the solar radiation is considered uniform on the PV panel. Based on the above assumptions, the temperature, thermodynamics constants as well as the optical properties are also uniform in each layer of the PV panel (Emmanuel, 2006).

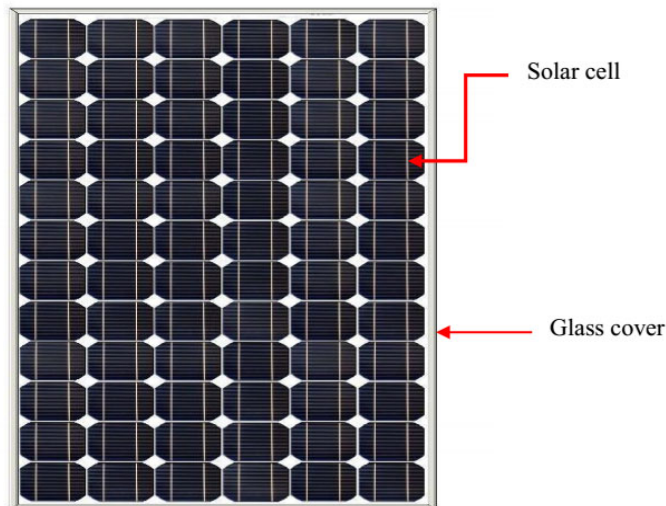


Figure 1: General view of a PV panel.

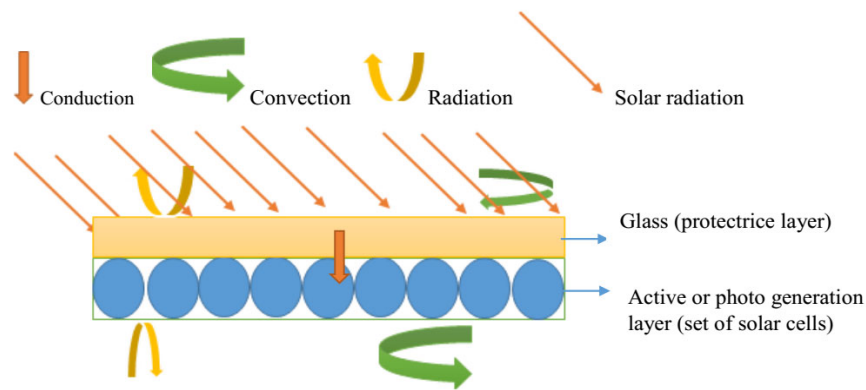


Figure 2 : Presentation of the Cross Section of a PV Panel with the various heat transfers

2.2. Energy balance of glass cover

Glass is the first layer of a photovoltaic panel. Owing to Tiwari *et al.* (2006), the energy balance through this layer is given by:

$$\alpha_g G(t) = U_{ga} (T_g - T_a) + U_{gc} (T_g - T_c) \quad (1)$$

in which the quantity T_c defines the temperature of the PV module while T_g and α_g designate the temperature and the absorption coefficient of the glass cover, respectively. Based on Eq. (1), one derives the temperature of the glass defined as

$$T_g = \frac{\alpha_g G(t) + U_{ga} T_a + U_{gc} T_c}{U_{gc} + U_{ga}} \quad (2)$$

where $U_{gc} = 1 / \left(\left(L_g / K_g \right) + \left(L_c / K_c \right) \right)$ and $U_{ga} = 1 / \left(h_{conv} + h_{rad} \right)$

In the previous relations, the parameter U_{gc} stands for the coefficient of thermal loss between the glass cover and the active zone whereas U_{ga} designates the coefficient of thermal loss between the glass cover and the ambient milieu.

In (2), the parameter $G(t)$ stands for the solar radiation intensity during the whole day. In scientific reviews, there are several models of solar radiation intensity existing such as Adnot (Ionel *et al.*, 2015), Karsten (Kasten *et al.*, 1989), Haurwitz (Ionel *et al.*, 2015) and Empirical model (Paulescu *et al.*, 2003). It has clearly appeared that the model of Adnot is the best since it describes the dynamics of the solar radiation nearest the reality. Then, this model is considered during our investigations and is expressed as follows (Ionel *et al.*, 2015):

$$G = 951.39 \sin(\alpha_s)^{1.15} \quad (3)$$

in which $\sin(\alpha_s) = \sin(\delta) \sin(\varphi) + \cos(\delta) \cos(\varphi) \cos(w)$, wherein φ is the latitude of the considered location and δ represents the declination of the Earth. The parameter w defines the position of the sun in the sky at any time and is expressed as follows:

$$w = 15 \times (12 - T) \quad (4)$$

where T represents the time.

2.3. Energy balance in the PV module

In the literature, nonlinearity generates new harmonics in a given dynamical system, offers a good advantage and is used to produce chaotic behavior, masking of the information. Beyond these applications, nonlinearity offers very often advantages in providing energy in a system (Dongo *et al.*, 2014; Pelap *et al.*, 2016). Motivated by this positive effect, we replace the constant absorption coefficient of the PV module by a nonlinear absorption coefficient expressed as a quadratic function of the temperature, since the variation of this coefficient due to the joule effect is usually neglected:

$$\alpha_c = \alpha_{c0} (1 + \beta T_c + \theta T_c^2) \quad (5)$$

wherein θ is the quadratic coefficient consequently chosen. The quantities α_{c0} , T_c and β are, respectively, the normalized thermal absorption coefficient, the temperature of the PV module and the coefficient of thermal linear expansion of the material (Dongo *et al.*, 2014; Fouad *et al.*, 2012).

In the active zone of the PV panel known as PV module, many processes take place like photo generation,

diffusion and recombination of minority carriers. The rise of the temperature of the PV panel is mainly linked to this zone. According to Tiwari *et al.* (2006), the energy balance at this layer is given by

$$U_{gc}(T_g - T_c) + \tau_g \alpha_c \beta_c G(t) = h_{cp}(T_c - T_a) + \tau_g \alpha_c \beta_c \eta_c G(t) \quad (6)$$

With $h_{cp} = \frac{1}{\frac{L_c}{K_c} + h_{conv}}$; $h_{rad} = \frac{\varepsilon_g \sigma (T_g^2 + T_{sky}^2)(T_g + T_{sky})(T_g - T_{sky})}{(T_g - T_{am})}$ and $h_{conv} = 5.7 + 3.8V$

In equation (6), V designates the wind speed, h_{conv} is the convective transfer coefficient, h_{rad} represents the radiative transfer coefficient and h_{cp} defines the coefficient of thermal loss between the PV module and the ambient milieu. The quantities τ_g , α_c , η_c , L_c , K_c , T_{am} , T_{sky} and β_c refer, respectively, to the transmission coefficient of the glass, the absorption coefficient, the electrical efficiency, the thickness, the thermal conductivity of PV module, the ambient temperature, the sky temperature and the packing factors designating the fraction of the PV module covered by the glass layer. Substitution of expressions (5) into Eq. (6) leads to the following relation:

$$AA T_c^2 + BB T_c + CC = 0 \quad (7)$$

in which we have put:

$$AA = -\tau_g \alpha_{c0} \beta_c \theta (1 - \eta_c) G(t) \quad ; \quad BB = h_{conv} + U_1 - \tau_g \alpha_{c0} \beta_c \beta (1 - \eta_c) G(t)$$

$$CC = -(\tau_g \alpha_{c0} G(t) - \eta_c \tau_g \alpha_{c0} G(t) + PF_1 \alpha_g G(t) + U_1 T_{am} + h_{conv} T_{am}) \quad ;$$

with $PF_1 = U_{gc} / (U_{gc} + U_{ga})$ and $U_1 = U_{ga} U_{gc} / (U_{gc} + U_{ga})$

Resolution of Eq. (7) yields two mathematical solutions for the temperature for the PV module and the accepted physical solution is defined below.

$$T_c = \frac{-BB + \sqrt{BB^2 - 4 \cdot AA \cdot CC}}{2 \times AA} \quad (8)$$

Fortunately, the MATLAB environment offers the possibility to forward the study and examine the contribution of the nonlinear absorption coefficient on the dynamics of the PV module

3. Results and Discussion

3.1 Effect of a nonlinear absorption coefficient on the glass cover

In this subsection, we conduct numerical simulations of the mathematical expression (2) of the temperature of the glass cover in the MATLAB environment. These investigations of the thermal behavior of the glass cover are carried out for both constant and nonlinear absorption coefficients as shown on figure 3. The curves are obtained for various values of quadratic coefficient θ with the following system parameters: $\alpha_g = 0.05$, $\tau_g = 0.95$ and $T_{am} = 298.15K$. We treat the case of the silicon PV module materialized by the values of $\alpha_{c0} = 0.95$ and $\beta = 2.6 \times 10^{-6} K^{-1}$. For the constant absorption coefficient (in black color on figure 3), we note that the profile of the temperature of the glass cover follows that of the solar irradiation. It could be also noted that the maximum temperature is around $345^\circ K$ (i.e., $70^\circ C$) at the midday. However, for various values of the nonlinear absorption coefficient (θ), we remark that the shape of the obtained curves (in color on figure 3) does not change. It also appears that the value of the maximum temperature decreases as the parameter θ grows. According to these results, the nonlinear character of the absorption coefficient plays the role of a cooling system for the glass cover.

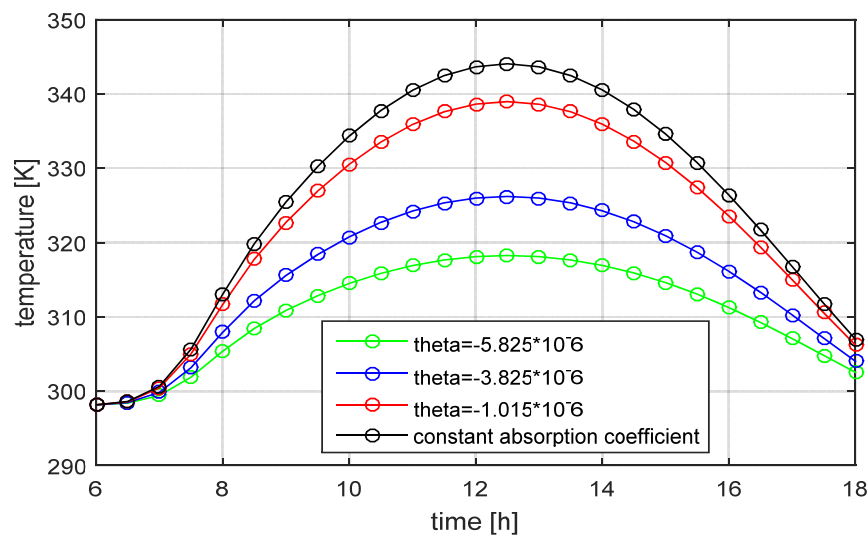


Figure 3: Glass cover temperature versus time for constant and nonlinear absorption coefficient made with the system parameters: $\alpha_{c0} = 0.95$, $\beta = 2.6 \times 10^{-6} K^{-1}$, $\alpha_g = 0.05$, $\tau_g = 0.95$, $T_{am} = 298.15K$. The presence of the nonlinear absorption coefficient of the PV module reduces the temperature of the glass cover.

3.2 Effect of a nonlinear absorption coefficient on a PV module

Figures 4-5 show variations of both the temperature and the electrical efficiency of the PV module using the parameters and conditions of figure 3. Numerical simulations of the mathematical expression (8) of the temperature of the PV module are made under MATLAB environment. In the case of constant absorption coefficient plotted in black color on figure 4, we observe that the maximum temperature of the PV module is closed to 70 degrees, but remains slightly higher than the temperature of the glass cover obtained in the same conditions (Swapnil *et al.*, 2009). Indeed, this difference of temperature is linked to the smallness of the heat capacity of the glass compared to that of the active zone known as PV module. Furthermore, several processes like recombination effect take place in a PV module. In fact, this recombination effect contributes also to the rise of the temperature of that layer thanks to the joule effect (Ibrahima *et al.*, 2016).

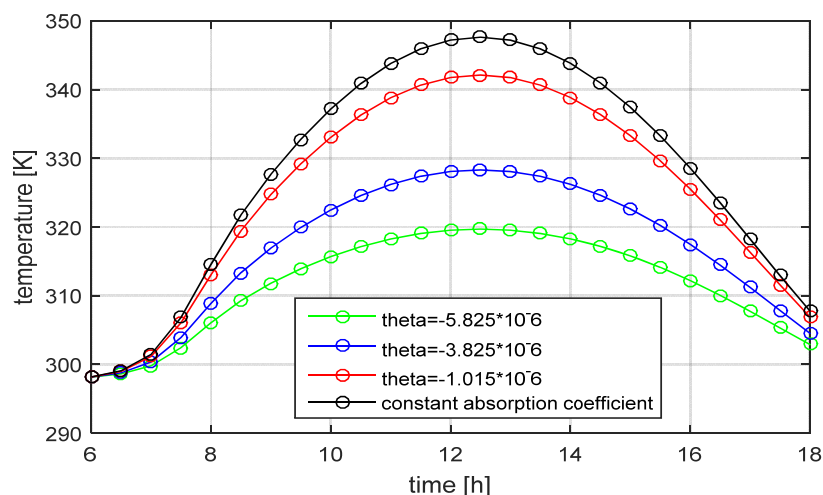


Figure 4: Variation of the temperature of a PV module for constant and nonlinear absorption coefficient obtained with same system parameters as in figure 3. The presence of the nonlinear absorption coefficient of the PV module reduces both the recombination effect in that zone and also its temperature.

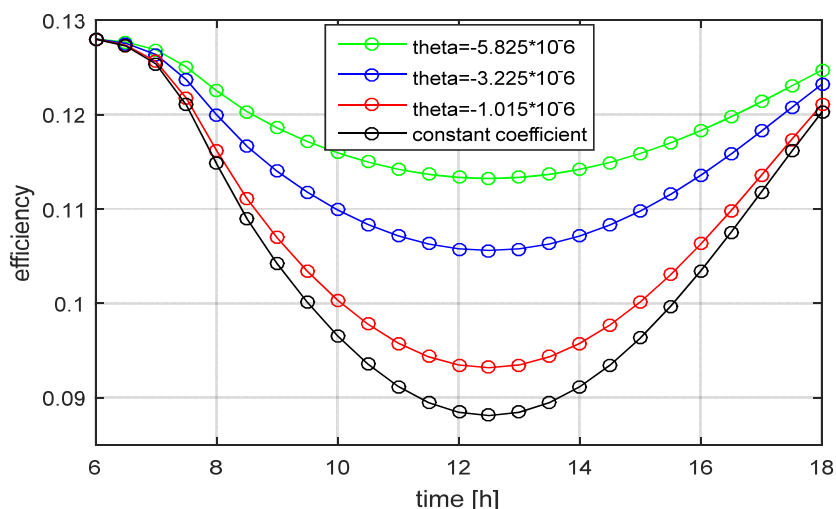


Figure 5: Evolution of the electrical efficiency of a PV module for constant and nonlinear absorption coefficient. The maximum electrical efficiency of the PV panel increases when the quadratic coefficient θ decreases.

However, by taking into account the nonlinear behavior of the absorption coefficient of this layer, we note that the temperature of the PV module retains the shape of the solar radiation. Moreover, its maximum temperature decreases and reaches the minimum for $\theta = -5.825 \times 10^{-6} K^{-2}$ (Table 1). Indeed, this coefficient θ impacts positively on the thermal behavior of the PV module by reducing both the recombination effect taking place as well as its operating temperature. In addition, the curves of figure 5 display that the electrical efficiency of the PV module grows as θ diminishes (Table 1). These results are in good accordance with those established by Pelap *et al.* (2016) in which they proved the usefulness of the nonlinearity in the solar cell domain. Thus, the nonlinear absorption coefficient reduces both the temperature and the recombination effect of a PV module and therefore increases its electrical efficiency.

Table 1. Numerical data collected on each layer of the PV panel at the turning point for various values of the quadratic coefficient θ .

Quantity Identification	Corresponding Value			
Quadratic coefficient $\theta \times 10^{-6} (K^{-2})$	-5.825	-3.825	-1.015	0
Temperature of the glass T_g (Kelvin degree)	319	327	339	342
Temperature of the PV module T_c (Kelvin degree)	320	329	341	347
Electrical efficiency (%)	11.32	10.56	9.31	8.81

4. Conclusion

In this paper, we have analyzed theoretically the effects of a thermal nonlinear absorption coefficient on the dynamics of a PV panel. This coefficient is expressed as a quadratic function of the temperature of the PV module known as the electronics active part of a PV panel. Based on the energy balance equation, the mathematical expressions of the evolution of the temperatures in each layer of the PV panel are determined. Numerical investigations carried out thanks to the MATLAB environment have exhibited some new features. Indeed, our findings have revealed that the nonlinear character of the absorption coefficient induces the cooling of the PV panel, reduces the recombination effects and therefore increases the electrical efficiency of the PV panel, for the nonlinear thermal coefficient θ chosen between $-5.825 \times 10^{-6} K^{-2}$ and $-1.015 \times 10^{-6} K^{-2}$. The above results offer to the manufacturers of PV panel a new trick to improve the electrical efficiency of the PV modules and reduce both their operating temperatures and recombination effects. For future works, we plan to study other nonlinear aspects of a PV panel.

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