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Multi-physics modeling and simulation of heat and electrical yield generation in photovoltaics

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ABSTRACT

Photovoltaic (PV) cells convert only a small part of solar energy into electricity. The rest of solar energy is dissipated into heat leading to an increase of PV cells temperature. It is well established that temperature increase negatively affects the electrical yield of the cells. As PV panels are constituted of several PV cells which are mounted in series or parallel, the PV panels' efficiency is therefore damaged by the increase of temperature. To study the coupled electrical yield and thermal behavior of PV panels, multi-physics models were developed. The models generally combine an electrical model with a thermal one. However, the photons wavelength effects are not accounted for in most of the models proposed in the literature. To account for this, we propose to use the Markov chain process for building an optical model. Therefore, the proposed multi-physics approach was developed by coupling three models: optical, electrical and thermal models. This proposed multi-physics approach was numerically implemented in the MATLAB software. The model was next applied to commercial silicon PV panels to predict their electrical and thermal behavior under Normal Operating Conditions Temperature (NOCT) conditions. The predicted results are compared to the manufacturer data sheets to validate the model. Finally, The thermal and electrical behaviors were also predicted under different irradiance levels.

1. Introduction

In order to decrease fossil energy dependence, government policies were adopted to develop and/or promote the use of renewable energies, which are produced from different natural resources: Earth's internal heat, wind, water or sunlight. Sunlight is the most abundant energy source available and thus, photovoltaic (PV) technology is one of the leading alternatives for harvesting solar energy and converting it into electricity. Most of produced PV modules (panels) use silicon cells technology, due to its ease of manufacturing and lower cost. However, like other cell types, silicon cells convert only a small part of the absorbed solar spectrum into electrical current. Several factors affect or reduce PV cells efficiency. One of the factors that significantly affect silicon PV cells efficiency is the operating temperature.

For silicon PV cells, several empirical relations are used to describe the decrease of the electrical efficiency with the increase of the PV cell operating temperature. A review of these relations is presented in Skoplaki et al. [1]. Most of them are close to the linear expression found in the work of Evans and Florshuetz [2]. The relations presented in Skoplaki's work [1] allow to predict the decrease of electrical efficiency (a loss in the electrical output power) when the operating temperature increases due to heating produced by the PV cell. Various parameters have an influence on the operating temperature such as: the weather conditions (irradiance level, ambient temperature and wind speed), materials properties (thermal dissipation and absorption properties of the different PV panel layers) and installing conditions of the PV panel. Moreover, the temperature variations to which the PV cells are subjected lead to cracks and thus deteriorate their electrical performance. It is therefore essential to correctly predict the operating temperature of PV panels and/or cells.

Several methods were developed to calculate the operating temperature of PV cells/panels taking into account the environmental conditions. The basic methods are built on a simplified energy balance equation with parameters that are empirically determined. For instance, Mattei et al. [3] estimated the temperature of a commercial multi-crystalline PV panel considering wind speed. However, in Mattei's work [3], the temperature was considered uniform in the panel and the irradiative heat exchanges were neglected. In the one dimensional numerical model proposed by Notton et al. [4], the PV panel is divided in three regions (front glass cover, PV cell and back glass cover). For each layer, an energy balance equation was built using an electrical analog model where temperatures, flows, flow sources and imposed

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temperatures were respectively assimilated to potentials, currents, current generators and voltage generators. The temperature variations in each layer were predicted by the finite difference method. In the work of Notton [4], different thermal conditions taken from literature were investigated, and particularly the influence of convective transfer coefficients. Armstrong and Hurley [5] proposed also a thermal model based on an electrical analogy. The thermal properties of the different PV panel layers were correlated with electrical components of a Resistance–Capacitance (RC) circuit. The modeling proposed by Armstrong [5] was validated by measurements of a PV panel under varying wind speeds. However, the irradiative heat losses were neglected. A thermal balance equation for a PV panel was proposed by Jones and Underwood [6]. The convection and radiation heat exchanges with front and rear panel surfaces are introduced in the rate of temperature change proposed in Underwood's work [6]. The PV panel temperature was predicted with a reasonable accuracy in Underwood's work [6]. The works presented above are mainly focused on predicting the temperature of the PV panel under varying meteorological conditions.

In order to assess operating temperature, electrical output power and then the corresponding performance or efficiency of the PV panel/cell, it is needed to develop thermo-electrical modeling. The thermo-electrical modeling combines an electrical model with a thermal one (see the works of Roger and Maguin [7] or of Tina and Scrofani [8]). Thus, the impact of outdoor variables is introduced in the electrical behavior predictions of the PV cells. However, the incident solar irradiance is considered to contribute totally or partially (via a correction factor) to generation of photovoltaic current. For example, in the works of Siddiqui et al. [9] and of Sánchez Barroso et al. [10], the heat generation per unit volume inside the PV panel is estimated as:

$$Q = S(1-\eta_{PV})\frac{A}{V} \tag{1}$$

where S is the incident solar irradiance, η_{PV} the electrical efficiency of PV cell, A the front PV panel area and V the volume of the PV cells in the panel. We note that the use of Eq. (1) requires the a priori knowledge of the efficiency. Furthermore, the electrical behavior is described with a PV cell equivalent circuit (classical one-diode model) in Siddiqui and Sánchez-Barroso's works [9,10]. However, Sánchez-Barroso [10] outlined that a detailed model, that fully integrates the optical, thermal and electric parts, must be developed to accurately predict the PV panel physical behavior.

A detailed multi-physics and numerical modeling is proposed by Vaillon et al. [11] to predict the photoelectric conversion of silicon made cells. The modeling proposed in Vaillon's work [11] accounts for operating conditions such as temperature and solar irradiance. It can also be used as a design tool. However, the encapsulation of the PV cell was not considered in Vaillon's work [11]. Following that framework, Weiss et al. [12] proposed a bi-dimensional modeling where the different physical phenomena (optical, electrical and thermal) are coupled. The work of Weiss [12] was mainly focused on radiation heat transfer in a PV panel. The temperature predictions were performed with a commercial finite element code. They are in fair agreement with the experimental value measured during one day. Recently, Migliorini et al. [13] highlighted that the behavior of PV panel can be dynamically characterize with a multi-physics model when weather data are available. However, the temperature field prediction inside the PV panel leads to a large system of equations that are computationally expensive to solve. Consequently, to reduce computational cost, a multi-physics approach leading to a set of equations that can be rapidly solved is needed.

The main objective of our work is to propose a multi-physics (optical, thermal and electrical) approach that predicts accurately the produced electrical power and the heat sources as a function of solar irradiation conditions and of meteorological conditions. But, the model must be built in a simple way to be used under dynamic variations of weather conditions. A one- dimensional multi-physics model was thus developed in this work. First, an optical modeling based on the work of Aljoaba et al. [14] evaluates the absorption of solar radiation in the glass, the encapsulation, and in the PV cell. It is based on the Markov's chains theory where the optical and geometrical properties of the materials (that are used in the PV panel) are integrated. Next, knowing the part of solar irradiance that is converted to heat and the surrounding conditions on the PV cell, the thermal modeling that was presented in the previous work of Sánchez-Barroso [10] estimates the temperature distribution throughout the thickness of the PV panel. At last, knowing the part of solar irradiance that is absorbed and the temperature inside the PV cell, the I–V curve and also the electrical output power are predicted. The electrical modeling is based on an equivalent one-diode electrical circuit. All the models are coupled sequentially and are numerically implemented in commercial software (MATLAB®). The models are detailed in the following sections.

2. Multi-physics modeling

2.1. Thermal modeling

The thermal model used in this work is based on the one proposed by Sánchez Barroso et al. [10]. The three main heat transfer modes (radiation, conduction and convection) are taken into account in the model. Ohmic heating was not considered in the model, since it has a negligible effect on the thermal behavior of the PV panel [15]. The governing equation of the thermal model is the classical heat transfer equation for a solid domain. In accordance with Sánchez-Barroso's work [10], the PV panel can be considered as a one-dimensional domain (the direction along the thickness of the PV panel). Thus, for each layer of the panel, the heat transfer equation can be written as:

$$\rho C_p \frac{\partial T(x,t)}{\partial t} = k\frac{\partial^2 T(x,t)}{\partial x^2} + Q \tag{2}$$

where ρ is the density, C_p the specific heat capacity, k the thermal conductivity, t the time, x the depth distance from the irradiated surface, $T(x,t)$ the temperature at a given coordinate and time, and Q an internal heat source. The material constants C_p and k must be determined for each layer of the PV panel. Following the work of Sánchez Barroso et al. [10], the heat transfer equation, Eq. (2) is solved numerically with a finite difference approach (first-order central finite difference scheme combined with implicit time integration rule).

To complete thermal modeling, boundary conditions must be added to the model. These boundary conditions are the thermal fluxes produced by convection and/or radiation of the front and rear PV panel surfaces with the environment. In this work, the front surface of the PV panel is assumed to be submitted to forced convection while the rear surface to free convection. Moreover, the radiation exchanges of the front surface to the sky or ground is accounted for. The radiation exchanges with the rear surface are neglected. The expressions of equivalent coefficients that account for the convection and radiation heat exchanges are reported in Appendix A.

Finally, the internal heat sources must be estimated for the different layers of the PV panel. For the glass and the encapsulation (EVA) layers, the internal heat source is defined as:

$$Q = \int_{\lambda_1}^{\lambda_2} a(\lambda) I_{rr}(\lambda) d\lambda \tag{3}$$

where λ is the wavelength of the photons, $a(\lambda)$ is the value of absorption coefficient of the layer at a certain wavelength λ, $I_{rr}(\lambda)$ the global solar irradiance that depends on a set of conditions (location, time and weather) and λ_1- λ_2 the useful range of wavelengths of solar spectrum. The starting value λ_1 of the useful range of wavelengths is taken equal to 300 nm, whereas the ending value λ_2 is defined with respect to the band gap energy value of silicon (which is a function of temperature). The absorption coefficient values $a(\lambda)$ in are evaluated with the optical