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A computational analysis of coupled thermal and electrical behavior of PV panels

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ABSTRACT

In this work, the objective is to develop a simple approach for the prediction of temperature and electrical efficiency of a PV panel. This modeling work constitutes a basic task towards better understanding of the behavior and capabilities of a PV panel when it is subjected to changing meteorological conditions. Different approaches may be used to determine the thermal response of a PV panel depending on the level of details needed for the temperature distribution. For a through-thickness temperature distribution, a one dimensional analysis is necessary. Therefore, only a one-dimensional finite difference model is proposed. Three different formulations of boundary conditions were used and compared in the numerical simulations. To build a full approach for thermal and efficiency analysis, the proposed thermal model is coupled with a solar radiation model and an electrical model. The parameters of the electrical model were estimated by the particle swarm optimization algorithm. Numerical simulations were performed with the meteorological inputs from Ajaccio (France) and for a commercial PV panel BP 350 U. The predictions were compared to existing models and to experimental results.

1. Introduction

Photovoltaic panels (called PV panels in the following) are composed of photovoltaic cells ("PV cells") mounted in series or parallel as modules. They are used to convert the solar energy coming into electrical current. They possess several advantages such as an easy mounting and installation procedure and they do not require sophisticated maintenance. The ability to generate electricity from a natural and vast renewable source makes PV panels a very interesting and promising option to fulfill part of the population's energy consumption, which according to Razykov et al. [1] will be triplicated in about 40 years, up to 30 terawatts in 2050. For such reason, research is a drive forward to improve the efficiency of PV cells. Unfortunately, mass produced PV panels are not yet at perfect conversion rate of the incident solar energy, even though they are more and more an advantageous solution to consider.

In accordance with the work of Armstrong and Hurley [2], the electrical power conversion efficiency for commercial PV modules is currently ranged between 13% and 20%. Consequently, only a small portion of the solar energy absorbed by the PV cells is converted to electricity while the remaining part is converted into heat, which leads to an increase of the PV panel temperature. Skoplaki and Palyvos [3] reported various empirical relations between electrical efficiency and PV panel temperature. From such relations, it can be noticed that an increase of PV panel temperature leads to a decrease of electrical efficiency. Therefore, the PV panel (or PV cell) temperature is a key parameter that must be controlled or decreased in order to achieve a better energy conversion efficiency of the PV cells and thus, a better PV panel performance. However, knowing the manufacturer (data sheet) given cell efficiency is not enough. If the requirement is to know how much energy could be actually obtained from a PV panel, the ambient conditions and the characteristics of the panel should also be taken into account. Therefore, a numerical model capable of integrating the electrical efficiency, the ambient conditions and the panel characteristics is the key to predict, under service conditions, a good estimate of the energy production capabilities of the PV devices.

Several different models were developed to predict the thermal response of a PV panel. A brief summary of different thermal models from the literature is given by Siddiqui et al. [4]. Jones and

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Underwood [5] proposed a thermal model for PV panels based on the energy balance equation. In their model, the rate of temperature change is expressed as a sum of convection and radiation heat transfer from the front and rear surfaces of the panel. The thermal model proposed by Jones and Underwood [5] is found to be accurate in clear and overcast conditions. Notton et al. [6] proposed a Finite Difference (FD) model with nodes that represent volumes assumed isothermal. The PV cell temperature is calculated at each node by applying an energy balance equation. With their numerical model, Notton et al. [6] tested various thermal hypotheses found in the literature. The influence of convective transfer coefficients is particularly investigated by Notton et al. [6]. Their numerical predictions are validated using experimental data. Armstrong and Hurley [2] proposed a thermal model that correlates the thermal properties of the PV panel layers with their electrical equivalent by means of a Resistance–Capacitance (RC) circuit. Armstrong and Hurley [2] investigated the influence of varying wind speeds on the PV panel back temperature. Recently, La Brano et al. [7] were able to predict the temperature throughout thickness of the studied device. However, the above mentioned thermal models are only one-dimensional models. A two-dimensional thermal model was developed by Caluianu and Băltăreţu [8] in order to predict the temperature field of PV panel mounted at different distances from a wall. In the numerical work of Caluianu and Băltăreţu [8], the Galerkin Finite Element (FE) approach was used. With this two-dimensional model, the velocity and temperature of air flow between the rear side of PV panel and the wall were predicted. In order to predict the thermal behavior of PV panels with or without cooling, Siddiqui et al. [4] developed a three-dimensional (3D) thermal model using the commercial FE code ANSYS. The effects of changing atmospheric conditions (Middle East climate conditions) and of operating conditions were studied by Siddiqui et al. [4]. Furthermore, they coupled their thermal model with a radiation and an electrical model to predict the thermal and electrical performance of a PV panel with and without a cooling system. Recently, the FE thermal model developed by Siddiqui et al. [4] was sequentially coupled with a structural FE model to predict the performance and the life span of different PV panels (see Hasan and Arif [9]). Most of the numerical studies cited above were focused on calculating the thermal response of a PV panel under varying ambient conditions. In the above-mentioned studies, different assumptions were used to calculate the convective heat transfer coefficients, the radiative heat exchange coefficients and the heat generation inside the panel. The thermal inertia of the panel is usually a key characteristic (Time Constant, see Armstrong and Hurley [2]), it cannot be neglected given the time the panels take to cool down or heat up after any changes in solar irradiance or ambient temperature.

In this work, we propose a coupled approach to predict the thermal and efficiency behavior of PV panels under varying meteorological conditions. In order to predict, in a simple and accurate way, the temperature field inside a PV panel, a one-dimensional (1D) FD thermal model was developed in this work. Accuracy of thermal fluxes is difficult to achieve and thus the definition of thermal boundary conditions is of prime importance – as it was discussed for example by Sartori and Armstrong and Hurley [10,11]. Three different sets of boundary conditions are taken into account in the current work. The sets of boundary conditions are those used by Notton et al. [6], Armstrong and Hurley [2] and by Siddiqui et al. [4]. However, the proposed FD model could be easily adapted to other descriptions of the boundary conditions. The main purpose in this work is to identify, on the thermal response, the influence of different heat exchange assumptions for these three different sets of thermal boundary conditions. Moreover, this modeling is intended to be a first step towards thermal efficiency computation and thermo-mechanical degradation prediction of a PV panel. The FD model can also be later improved towards more realistic thermal simulation of the PV panel, either by taking into account complex thermal environment or by increasing the dimensions of the analysis, as it was both done by Natarajan et al. [12] with 3D FE thermal simulation of complex solar cells.

In addition, the proposed thermal model is sequentially coupled with two additional models to form a multi-physics model capable of predicting the thermal and electrical response of a PV panel. The first additional model used to determine the amount of solar energy absorbed by the PV panel and is known as the radiation model. The second additional model is used to predict the *I–V* curve at a specific operating point and it is known as the electrical model. In this work, the electrical model is based on the well-known one-diode electrical analogy (based on the expressions given by Siddiqui et al. [4] and Tsai [13]). The required electrical parameters are calculated using a developed optimization method based on the movement of swarms [14]. A complete description of the models implemented in this study is given in the following section.

2. Multi-physics modeling of PV panels

A multi-physics model is proposed in this work to study the thermal response of a PV panel while it works under continuously changing ambient conditions. The model sequentially couples a solar radiation model that calculates the amount of solar energy absorbed by the PV cells, a thermal model that calculates the heat fluxes inside the PV panel and the heat interactions with the surroundings and, finally, an electrical model capable of determining the electrical performance of the panel at a given operating point.

2.1. Solar radiation model

The objective of the solar radiation model is to calculate the amount of solar radiation absorbed by the PV cells. This determines in turn the amount of energy available for electrical conversion in the cells. The main input is the measured solar radiation flux, taking into account its direct beam and diffuse components. The model selected for this study is used in the work of Notton et al. [6], based on the ASHRAE convention. The absorbed solar radiation S is estimated by the equation [15]:

$$S=(\tau_{fg}\alpha_{PV})_n\left[R_bG_bK_b+G_dK_d\frac{1+\cos\beta}{2}+(G_b+G_d)\rho_{ground}K_{ground}\frac{1-\cos\beta}{2}\right] \quad (1)$$

where $(\tau_{fg}\alpha_{PV})_n$ is the normal transmitivity – absorptivity product (the term "normal" represents a zero incidence angle), R_b is the ratio of beam radiation on tilted plane to beam radiation on horizontal plane, G_b the beam solar radiation flux on a horizontal plane, G_d the diffuse solar radiation flux on a horizontal plane, K is the incidence angle modifier for the beam, diffuse and ground-reflected radiations, ρ_{ground} the reflectivity of the ground (also called albedo) and β is the tilt angle of the panel (see the schematic representing the panel in Fig. 1). The ratio of beam radiation on the tilted plane to that on the horizontal plane R_b is calculated as follows:

$$R_b=\frac{\sin(\alpha+\beta)}{\sin(\alpha)} \quad (2)$$

where α is the elevation angle and β is the tilt angle of the PV panel (see Fig. 1). The elevation angle α is calculated with the