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Two-dimensional finite difference-based model for coupled irradiation and heat transfer in photovoltaic modules

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ABSTRACT

Simulation of a complete PV system shall stem from a Multiphysics perspective. Within a continuum modeling approach, among these physics, the thermal model of a PV panel is most crucial because all the other models are directly or indirectly related to it. As all models of a PV system are connected sequentially, error from one model component propagates to the next model component and the overall system error accumulates eventually. One of the main objectives of this work was to increase the prediction accuracy by developing a fully transient 2-D finite difference (FD) based thermal model. The developed computational code is completely generic and can be applied to any type of PV technology or configuration. It was shown in the study how to choose an appropriate grid size for any FD model. Using the developed code, various studies were also conducted. Modified radiation models, heat transfer coefficients and thermal networks for the PV panel were proposed in the study, which remarkably improved the accuracy of the thermal model. Also studied were the effects of including heat transfer from the sides of a PV panel and heat generation in the front glass cover. The results showed that ignoring the heat transfer from the sides of a PV panel and including heat generation in the front glass cover have no noticeable difference in the model prediction.

1. Introduction

Solar energy is one of the most widely spread renewable energies source. Energy from the sun can be harvested by direct or indirect methods [1]. Photovoltaics (PV) is a process of converting solar radiation directly into electric current. PV cells are the fundamental building blocks of a PV system. A single silicon cell produces only up to about 3–4 W of electric power under standard test conditions (STC), which is insufficient for most practical applications. For this reason, PV cells are grouped together either in series or parallel, depending on power requirements [2]. In 2015, crystalline PV cells constituted 96% of the total global annual PV production [3].

PV technology, unlike other renewable energy sources, has an advantage of being easily accessible and employed, both at small and large scale. One needs to completely model the PV system to accurately predict the overall performance under service conditions. A robust PV system model is a multi-physics model that usually consists of radiation model, thermal model, electrical model and in some cases, structural model. The most important measure of a PV system is its power output. It needs certain parametric inputs and one such parameter is the temperature of the PV cell under operation, which can be calculated using a thermal model.

Electrical power conversion efficiency of most commercial panels nowadays ranges between 13% and 20% [3]. Field conditions are very different from these STC and are very dynamic. The portion of absorbed radiation that is not converted to electric current, builds up to produce unwanted heat [4]. It is a well-established fact that with an increase in the temperature of silicon PV cells, there is a linear drop in the efficiency [5]. Thus, knowing the rated efficiency of a PV panel is not sufficient to estimate the total power produced in service conditions. One also needs to know ambient conditions and the characteristics of the panel.

Jones and Underwood [6] developed an analytical thermal model to predict the temperature of PV cells, with changing environmental conditions. Due to the assumptions of their model, including that the whole panel is at uniform temperature, the predicted temperature varied from the experimental temperature by almost 6 °C. Their model was more accurate in clear sky conditions with less irradiation fluctuations, thus highlighting a slower response to changing environmental conditions. Tina and Scrofani [7] developed an analytical model

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Abbreviations: ARC, anti-reflecting coating; FD, finite difference; FE, finite element; NOCT, nominal operating conditions temperature; POA, plane of array; PV, photovoltaic; RMSE, root mean square error; STC, standard test conditions; STF, Solar Test Facility (Test Site in Doha, Qatar)

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to predict the cell temperature by taking into account only the glass, PV cells and back sheet layers, with an assumption that each layer is isothermal. It was shown by both of these analytical models that due to large thermal mass of a PV panel, steady-state and quasi steady-state models are not justifiable for an accurate temperature prediction. According to Guarracino [8], these approaches provide an overestimate and thus, a fully transient model with a fast response time is a must to capture the ever-dynamic behavior of a PV system. The thermal model developed by Armstrong and Hurley [9] correlates thermal exchange in different layers of a PV panel with an equivalent Resistance-Capacitance (RC) circuit and was used to measure the thermal response time of the PV panel due to its thermal mass. The model of King et al. [10] is expressed through an empirical equation that calculates cell temperature based on module's measured back surface temperature, incident irradiation, wind velocity and a PV technology-dependent temperature constant. The model is fairly accurate but requires a lot of input parameters, which vary according to the panel's characteristics.

Notton et al. [11,12] developed their own one-dimensional (1-D) Finite Difference (FD) transient model to solve the energy balance equations, between different layers of a PV panel. They also considered only the front glass, PV cells and the back-glass layer. A detailed study to find out the effect of various convective heat transfer equations on the accuracy of the results was also carried out. They concluded that neglecting the free convection and considering only the forced convection gives quite satisfactory results. Their model was also validated against the experimental data. Barroso et al. [13] followed the works of Notton et al. and Armstrong and Hurley by designing a front glass–PV cells–EVA–back sheet configuration in their model. It was shown that without any significant increase in computational requirement, the overall accuracy of the model improved. Lo Brano et al. [14] developed a 1-D FD code for a PV system coupled with phase change material "PCM"-based heat storage system. The difference between the calculated and measured temperatures was within a range of 7%. Zondag et al. [15] developed 1-D, 2-D and 3-D steady-state and quasi steady-state thermal models for hybrid photovoltaic/thermal (PV/T) systems. With an extensive study, they document the accuracy and computational resources with the increasing dimensions of their models. They also highlight the need of 2-D and 3-D for some design optimization purpose.

Caluianu and Baltaretu [16] developed a 2-D Finite Element (FE), while Lee and Tay [4] proposed a detailed 3-D FE model. Both of these models were used for steady-state analysis only. Acciani et al. [17] developed a 3-D FE model for PV cells (not panel). For finding accurate temperature of the cell, they included the effect of resistive heating along with heating due to irradiation. They concluded that most of the heating in a cell is due to solar irradiation alone. To simulate 3-D behavior, Siddiqui et al. [18] developed a 2-D shell element-based FE model. They studied the effect of changing ambient conditions on a PV system, both with and without a cooling system (PV/T). Unlike Notton et al. [11], they preferred using both free and forced convection, along with radiative heat losses from the front/rear surfaces of the PV panel. Their model was tested against the experimental data of a whole day irradiation and the root mean square error (RMSE) was reported to be 4.9 °C.

Like most FD codes, Chow [19] developed a FD thermal model for PV/T systems based on explicit time scheme. It was shown that as a PV system is very dynamic, a transient model is compulsory for accurate prediction. Tsai [20] also used explicit time scheme to derive the cell temperature. A detailed review from Skoplaki and Palyvos [21] summarizes the pros and cons of several implicit and explicit empirical correlations found in the literature. Explicit FD methods are more accurate, as they calculate the future temperature based on present temperature. But, the time step size by which the solution advances forward in time is restricted by the choice of the node size. On the contrary, implicit FD methods are slightly less accurate, but they do not have any such time step size limitation. This reason makes implicit FD methods more computationally advantageous, particularly where large numbers of nodes are involved.

One of the main aims of our currently presented work is to reduce the error in the thermal model. In this way, the propagation of the error in temperature should be limited towards subsequent multi-physics models of the devices. 1-D models give a good estimate for long-term performance measures, but higher dimensional models (2-D and 3-D) are needed for more accuracy [15]. 2-D shell models, like that used by Siddiqui et al. [18] can only take into account the heat transfer from the front/rear of the PV panels. Whereas in reality, the overall geometry of the sides has also a role to play taking into account the heat dissipation, and the absence of adiabatic conditions at the sides– i.e. edge effects. In the present study, a 2-D cross-sectional (or full-width through-thickness) model has been developed, so the heat transfer from the front/rear, as well as from the sides of the PV panel can also be taken into account.

To reduce the complexity of the model, most researchers like Notton et al. [11] and Tina and Gagliano [22] consider the different layers of a PV panel to be isothermal. Another common simplification researchers adopt is to consider just three layers of a PV panel, while usually ignoring the EVA binding layer. In the present work, the EVA layer has been included and no layer has been assumed to be isothermal. More details on PV panel layers are given in the next section. This approach ensures to capture proper temperature distribution contours.

In the present work, for thermal modeling, a self-developed FD numerical method with an implicit time scheme has been implemented. As mentioned earlier in the text, steady-state and quasi steady-state models provide an overestimate by ignoring the thermal mass of the PV panel [8]. For this reason, the model developed herein considers the thermal mass of each layer separately. Thus, it is fully transient and can easily be used for short-term (seconds to daily timescales), as well as long-term (monthly, yearly to life-span) calculations.

The developed model is completely generic and, with small modifications, can be used with any PV panel type, as well as configuration. In fact, a similar technique can be used for any 2-D body that experiences conduction, convection and radiation modes of heat transfer. Herein, only the PV panel structure has been considered, but the same approach can easily be extended to PV panels with cooling systems or heat storage systems attached to them [14]. As our model fully captures the temperature distribution through the thickness of the panel, it can also be used for studying the thermally induced cyclic stress-strain at the interface of different layers inside a PV panel [23]. The model can later be extended to 3-D, if the reduced error is worth the extra computational effort and complexity of the code. The model should also be extended as fully transient, unlike the 3-D FE models of Lee and Tay [4] and Natarajan et al. [24].

2. PV panel composition

The PV panel considered for this specific study is ND-220E1F from Sharp company [25]. It consists of poly-crystalline silicon PV cells. Like any other typical PV panel, it has six main layers. In this study, thinner layers like anti-reflecting coating (ARC) and back contact are assumed not to take part in heat transfer. This assumption is due to very small thermal resistance and thickness (capacitance) of these layers, as compared to other layers. Thus, only four materials have been taken into account here, namely – front glass cover, EVA binder, PV cells and Tedlar back sheet. The metallic frame (usually Aluminum) that envelops these layers from the sides is also not considered here. The schematic of the cross-section (or through-thickness) of the PV panel is shown in Fig. 1 and the properties of each layer considered is given in Table 1.

3. Prediction models

The purpose of the thermal model is to calculate the 2-D cross-