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Review of methods for the calculation of cell temperature in high concentration photovoltaic modules for electrical characterization

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The solar cell operation temperature is an important input in models for the electrical characterization of high concentration photovoltaic cells and modules. However, the direct measurement of this temperature is difficult in these kinds of devices. Because of this, in recent years, the scientific community has proposed different methods for indirectly calculating the cell temperature in high concentration photovoltaic modules from atmospheric parameters and/or easily measurable parameters on the module. In this paper, a comprehensive review of existing methods for cell temperature calculation in high concentration photovoltaic modules for electrical characterization is presented. The different methods are summarized and a comparative analysis is done. Required inputs, advantages and technical difficulties of each method are highlighted. Also, an experimental campaign has been carried out at Jaén, south of Spain, in order to quantify the accuracy of the methods. Results show that methods based on direct measurements on the module are somewhat more accurate than methods only based on atmospheric parameters. The choice of the most suitable method for a specific application will depend on the availability of module information, on the required accuracy and on technical issues.

Contents

Abbreviations: HCPV, high concentration photovoltaic; MPP, maximum power point; RMSE, root mean square error; ANN, artificial neural network

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1. Introduction

High concentration photovoltaic (HCPV) systems use optical devices (lenses or mirrors) to concentrate the sunlight onto small solar cells. Although there are a lot of possible configurations in order to implement this concept [1,2], a typical HCPV system consists of a two-axis solar tracker on which HCPV modules are mounted, each module composed of several electrically connected solar cells with their associated optics. The small size of the solar cells allows incorporating high efficiency III–V multi-junction solar cells, while other silicon-based solar cells can also be used [3]. One of the advantages of these systems is the high potential of costs reduction because they replace expensive semiconductor materials by cheaper optical materials [4]. As well, the operation with high efficiencies implies an increase of produced energy for the same installed area than a conventional photovoltaic system [5].

The operation temperature of the cells in an HCPV module affects its performance. This is because the band-gap of the semiconductors that compose the solar cells reduces when temperature increases. This implies a change in the solar cells electrical parameters: open-circuit voltage, fill factor, maximum power and efficiency decrease with increasing temperature, while short-circuit current increases (Fig. 1). These effects have been observed for both silicon-based solar cells and III–V multi-junction solar cells [6–9]. As HCPV modules behavior is influenced by the cells inside, HCPV modules electrical parameters are affected by temperature in the same way [10,11]. Thus, knowledge of the cell temperature is critical for characterizing the behavior of HCPV modules.

While cell temperature is an important input in models for the electrical characterization of HCPV cells and modules [12], the direct measurement of this temperature in HCPV modules seems to be difficult because it requires accessing inside the module and placing of a small temperature sensor very close to the solar cell [13]. Although in conventional flat-plate modules the cell temperature can be adequately estimated by measuring the temperature on the back of the module, in HCPV modules the complex thermal behavior and the use of heat exchangers for keeping the cell temperature in acceptable levels and avoiding degradation make difficult this practice [14,15]. Because of these difficulties, in recent years the scientific community has devoted efforts in developing methods for indirectly calculating the cell temperature in HCPV modules from different parameters (atmospheric parameters and/or easily measurable parameters on the module).

The cell temperature is not only important in the modeling of HCPV modules, but it has interest in the power rating of these devices. Conventional photovoltaic modules are rated at specific conditions of cell temperature, usually at 25 °C of cell temperature [16]. In contrast, HCPV modules are usually rated at defined conditions of environmental parameters due to the difficulty of measuring the cell temperature. For instance, the ASTM standard E2527-06 [17] requires ambient temperature of 20 °C, direct normal irradiance of 850 W/m^2 and wind speed of 4 m/s. Although establishing these conditions avoids the need of measuring cell temperature, the obtained rated maximum power is not directly comparable to that obtained for other photovoltaic technologies. This is an issue for market penetration of HCPV technology [18]. Thus, it would be desirable to have rating procedures based on standard cell temperature conditions [19] and methods that reliably calculate cell temperature.

In this paper, a comprehensive review of existing methods for calculating cell temperature in HCPV modules for electrical characterization is presented. Its aim is to help the photovoltaic researchers and professionals in the choice of the most suitable method for each application. The review comprises all the relevant contributions in this field, mainly developed in the last 3–4 years. Two remarks must be done:

There are a lot of methods for calculating the cell temperature in conventional flat-plate modules [20]. Among these methods, only methods that have been applied for HCPV modules are included in the present review.

In recent years, network thermal models have been proposed that predict temperature distributions across the module [21–25]. These models are oriented to thermal management and module design studies. As their implementation is complex, they are not intended for electrical characterization, so that they will not be included in the present review.

Taking this into account, the reviewed methods have been grouped according to the following classification: on the one hand, methods based on direct measurements on the module; on the other hand, methods based on atmospheric parameters. Furthermore, methods based on direct measurements have been divided into methods based on module heat-sink temperature and methods based on electrical parameters (Fig. 2). Methods based on direct measurements are expected to be more accurate than methods based on atmospheric parameters, while methods based on atmospheric parameters present the advantage that the cell temperature can be estimated at any location from meteorological data.

The paper is organized as follows: Section 2 is an overview of HCPV technologies; Sections 3, 4 and 5 summarize the methods for cell temperature calculation in HCPV modules according to the proposed classification: methods based on module heat-sink temperature (Section 3), methods based on electrical parameters (Section 4) and methods based on atmospheric parameters (Section 5); a comparative analysis of the methods from both a qualitative and a quantitative point of view is done in Section 6; finally, Section 7 presents the conclusions of the work.

It is important to remark that not every cell in an HCPV module exactly operates at the same temperature. Measurements on the back plates of HCPV modules have shown that cells near the frame have lower temperatures depending on wind speed and direction and orientation of the module [26,27]. Because of this, authors use to work with the "average cell temperature" in the module. This parameter will be simply referred in this paper as the "cell temperature" of the module (T_c).

2. HCPV technology overview

HCPV systems operate under light concentrations between 300 and 2000 suns [5]. These systems can be built with the participation of different conventional industrial sectors, such as glass, steel, aluminum