Solar Energy Materials & Solar Cells 124 (2014) 159–165

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

A method for estimating cell temperature at the maximum power point of a HCPV module under actual operating conditions

Eduardo F. Fernández *, P. Rodrigo, F. Almonacid, P. Pérez-Higueras

Centro de estudios Avanzados en Energía y Medio Ambiente, University of Jaén, Jaén, Spain

ARTICLE INFO

Article history:
Received 12 December 2013
Received in revised form
27 January 2014
Accepted 31 January 2014
Available online 21 February 2014

Keywords:
High concentrator photovoltaic
Cell temperature
Maximum power point
Mathematical method
Outdoor measurements

ABSTRACT

The operating cell temperature of a HCPV module or system is a key factor, because it directly affects efficiency and reliability. Hence, the accurate estimation of cell temperature in a HCPV module is crucial. Under real operating conditions, HCPV modules work at the maximum power point, because they are connected to an inverter. At the maximum power point, the cell temperature is lower than the cell temperature of open circuit, because solar cells are generating power which is not transformed into heat. At present, none of the existing methods are valid to estimate the operating cell temperature of a HCPV module connected to an inverter. In this paper, a procedure for estimating this temperature is introduced. The results show that the proposed method performs effectively in the estimation of the cell temperature in a HCPV module connected to an inverter. In addition, an analysis of the difference between the cell temperature of open circuit and the cell temperature at the maximum power point in a HCPV is conducted and a difference of up to 21 °C has been found.

1. Introduction

In the high concentrator photovoltaic (HCPV) modules, mirrors or lenses are used to concentrate light on a small and high efficiency solar cell, usually III–V multi-junction (MJ) solar cells [1–3]. This allows the solar cell area to be replaced by cheap optical devices to reduce the cost of energy generation. The high efficiencies expected for HCPV modules and MJ solar cells show that this technology could play an important role in the power generation market [4–8]. A typical HCPV system is formed by several HCPV modules interconnected in series and parallel mounted on a two-axis solar tracker and connected to an inverter [9,10,4].

Like the single junction solar cells, the electrical performance of the multi junction solar cells is affected by their temperature [11–13]. The cell temperature of a HCPV module has an important impact on its electrical output [14,15]. In addition, the operating cell temperature of a HCPV module or system is a key issue since it is directly related with its efficiency and reliability [16]. Hence, the estimation of the operating cell temperature of a HCPV module or system is critical for its electrical characterisation, energy prediction and thermal management [17].

Under actual operating conditions, HCPV modules are work at the maximum power point because they are connected to an inverter. At the maximum power point, HCPV modules generate power which is not transformed into heat. Because of this, the operating cell temperature of a HCPV module at maximum power point is lower than the cell temperature of open circuit. This has been noted in [18], where a difference between cell temperature of open circuit and cell temperature at the maximum power point up to 14 °C has been found.

Although there are several methods for estimating the cell temperature of a HCPV module [18–25] none of them can be used to estimate the operating cell temperature at the maximum power point of a HCPV module connected to an inverter. The methods presented in [18–23] need electrical parameters such as the short circuit current, the open circuit voltage, or the whole *I–V* curve of the HCPV module to be applied. These parameters are not available under actual operating conditions. Therefore, these methods are not useful to estimate the cell temperature of HCPV module working at the maximum power point. The methods presented in [24,25] are based on equations that allow the estimation of the cell temperature of a HCPV module from its heat-sink temperature. However, the mathematical expressions used do not take into account the generated power which is not transformed into heat when the HCPV modules are connected to an inverter. Hence, these methods are valid only when the HCPV module is in open circuit.

* Corresponding author. Tel.: +34 953213518; fax: +34 953212183.
E-mail address: fenandez@ujaen.es (E.F. Fernández).

http://dx.doi.org/10.1016/j.solmat.2014.01.050

Due to the above, the aim of this work is to introduce a method for estimating the operating cell temperature at the maximum power point of a HCPV module connected to an inverter. In order to validate the proposed method, the operating cell temperature of a HCPV module connected to an inverter has been measured. The goal is to introduce a valid procedure for determining the cell temperature of a HCPV module or system under actual operating conditions. In addition, a deep analysis of the difference between the cell temperature of open circuit and the cell temperature at the maximum power point of a HCPV module is conducted.

The paper is organised as follows. Section 2 describes the experimental set-up used to carry out this study. In Section 3, the method is described. The results obtained for the proposed method are shown in Section 4. In Section 5, a study of the difference between the cell temperature of open circuit and the cell temperature at the maximum power point is conducted. The main conclusions found and future work are presented in Section 6.

2. Experimental set-up

The study was conducted in the Centro de Estudios Avanzados en Energía y Medio Ambiente (CEAEMA) at the University of Jaen in southern Spain from August to December 2013. To carry out this study two HCPV modules prototypes of the same technology have been used. Fig. 1 shows a diagram of a single receiver of the HCPV modules. The main characteristics of the HCPV modules are shown in Table 1. In addition, the external quantum efficiency of the cells and the transmittance of the lenses of the studied modules are shown in Fig. 2.

The HCPV modules are mounted on a two-axis solar tracker designed by BSQ on the roof of the research centre (Fig. 3-top left). Also, a four-wire PT100 placed close to the solar cell on a concentrator receiver to measure the cell temperature (T_c) (Fig. 3-bottom right), and a four-wire PT100 placed on the back of the module, under the solar receiver, to measure the heat-sink base temperature ($T_{h\text{-}s}$) (Fig. 3-bottom left) in each of the studied modules have been installed. It is important to note that the temperature sensors are placed in the same receiver in both modules in order to avoid differences in the temperature due to the temperature distribution of a HCPV module. Furthermore, the sensors are located in a receiver between the centre and the border of the module, so that the measured temperatures can be considered as the average temperature of a receiver of the HCPV modules [26]. To record the cell and heat-sink temperature an Agilent 34970A data logger located in the laboratory has been used. In addition, there is an atmospheric station MTD 3000C from GEONICA to record other outdoor parameters such as direct normal irradiance (DNI), wind speed (W_s) and air temperature (T_{air}). This station is located on the roof of the research centre and is connected through the Ethernet with a PC located in the laboratory. In order to study the cell temperature at maximum power point, one of the modules was connected to a StecaGrid 300 inverter located in the laboratory Fig. 3. A data logger EM24 DIN records the maximum power (P_{max}) generated by the module among other parameters of the inverter. The other module was kept at open circuit to analyse the difference between the solar cell temperatures of both modules.

3. Method for estimating operating cell temperature at maximum power point

In this section, the procedure followed for calculating the cell temperature of the HCPV module connected to the inverter is introduced. The proposed method ascertains the cell temperature of a HCPV module from its heat-sink temperature and its generated power by the use of the thermal resistance of the module. Because of this, the description of the procedure followed to estimate the thermal resistance of the studied modules is also provided.

Table 1
Characteristics of the high concentrator photovoltaic modules used in the experiment. Every cell is protected with a bypass diode.

Geometric concentration	750
Primary optics	SOG squared flat Fresnel lens
Secondary optics	Reflexive truncated pyramid
Optical efficiency	0.80
Type of solar cells	Lattice-matched GaInP/GaInAs/Ge
Solar cells area	0.763 cm^2
Number of solar cells	20
Cooling	Passive

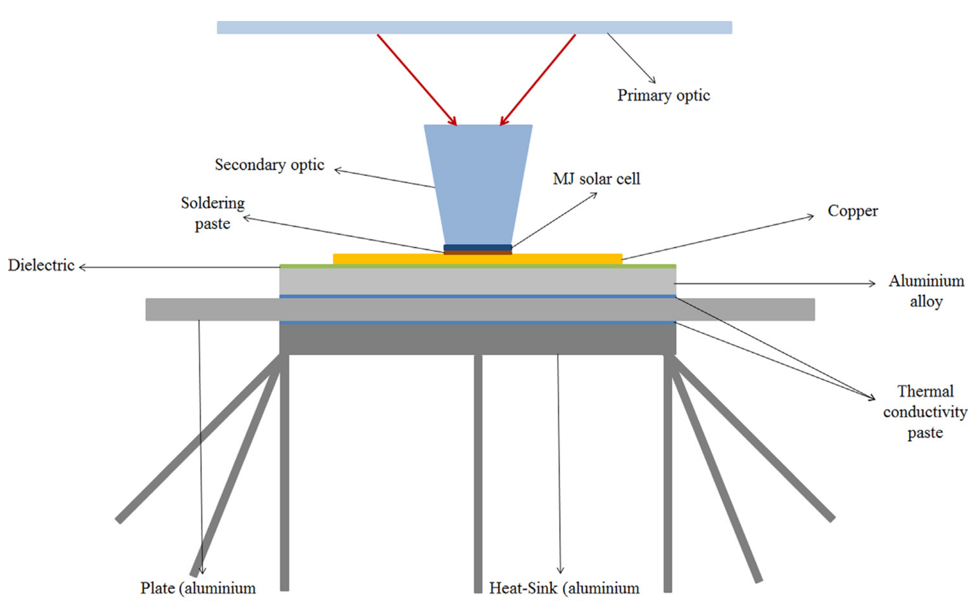

Fig. 1. Schematic diagram of a single receiver of the HCPV modules.