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

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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 are working 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 at 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 at open circuit and the cell temperature at the maximum power point in a HCPV is conducted and a difference of up to 21ºC has been found.

Keywords: High concentrator photovoltaic, cell temperature, maximum power point, mathematical method, outdoor measurements.

1. Introduction

In the High Concentrator Photovoltaic (HCPV) modules, mirrors or lenses are used to concentrate the light on a small and high efficiency solar cell, usually III-V multi-junction (MJ) solar cells [1, 2, 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, 5, 6, 7, 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, 12, 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 characterization, energy prediction and thermal management [17].

Under actual operating conditions, HCPV modules are working at maximum power point because they are connected to an inverter. At maximum power point, HCPV modules are generating 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 at open circuit. This has been noted in [18], where a difference between cell temperature at open circuit and cell temperature at maximum power point up to 14ºC has been found.

Although there are several methods for estimating the cell temperature of a HCPV module [18, 19, 20, 21, 22, 23, 24, 25] none of them can be used to estimate the operating cell temperature at maximum power point of a HCPV module connected to an inverter. The methods presented in [18, 19, 20, 21, 22, 23] need to know 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 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 only valid when the HCPV module is at open circuit.

Due to the above, the aim of this paper is to introduce a method for estimating the operating cell temperature at 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 at open circuit and the cell temperature at maximum power point of a HCPV module is conducted.

The paper is organized 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 at open circuit and the cell temperature at 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. Figure 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 figure 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-top right). 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 the 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.

3.1. Thermal resistance of the HCPV modules

In order to estimate the cell temperature at maximum power point from the heat-sink temperature of a HCPV module it is necessary to know the thermal resistance between the solar cell and the back surface of the module. This value can be theoretically calculated if a detailed knowledge of the materials between the solar cell and the back surface of the module are known [27]. However, the thermal resistance can also be obtained empirically from the internal thermal resistance which is defined as the thermal fall between the cell and the heat-sink of the HCPV module at open circuit through [25, 27]:

$$\rho = (T_c - T_{h\text{-}s})/DNI \quad (1)$$

where ρ is obtained by performing a linear regression analysis of ($T_c - T_{h\text{-}s}$) as a function of DNI of the HCPV module at open circuit with a value of $\rho = 0.0159$ K/Wm^{-2}.

Once the internal thermal resistance is known, the thermal resistance between the solar cell and the back surface of the module is finally ascertained as [27]:

$$R = \rho/(C_{geometric} \cdot \eta_{optical}) \quad (2)$$

where $C_{geometric}$ and $\eta_{optical}$ are the geometric concentration and optical efficiency of the module (see table 1) respectively, with a value of $R = 2.65 \times 10^{-05}$ K/Wm^{-2}.

3.2. Method description

The cell temperature of a HCPV module can be estimated from the heat-sink temperature as [27, 28]:

$$T_c = T_{h\text{-}s} + R \cdot \rho_P \quad (3)$$

where ρ_P is heat power density of the cell. The heat power density of a solar cell of a module connected to an inverter ($\rho_{P,Pmax}$) could be theoretically calculated as a function of DNI through the difference between the power density that falls on the solar cell from the primary optic ($\rho_{P,received}$) and the generated electrical power density ($\rho_{P,generated}$) as [28]:

$$\rho_{P,Pmax} = \rho_{P,received} - \rho_{P,generated} = DNI \cdot C_{geometric} \cdot \eta_{optical} - DNI \cdot C_{geometric} \cdot \eta_{optical} \cdot \eta_{cell} \quad (4)$$

where η_{cell} is the efficiency of the solar cell. This efficiency strongly depends on the direct normal irradiance, the cell temperature and the incident spectrum and its behaviour is difficult to model [29, 30, 31]. Because of this, the equation (4) presents an important uncertainty to calculate the heat power density of a cell under real operating conditions with an adequate degree of accuracy.

However, the generated electrical power density of a cell can be estimated as a function of the measured maximum power (P_{max}) generated by the HCPV module, the number of solar cells of the module (N) and the cell area (A_{cell}) (see table 1) as:

$$\rho_{P,generated} = P_{max}/(N \cdot A_{cell}) \qquad (5)$$

It is important to note that, due to the inherent mismatch among the cells in a HCPV module, this value should be considered as the average generated electrical power density of a cell of the HCPV module [32]. Taking this into account the equation (4) can be rewritten as:

$$\rho_{P,Pmax} = DNI \cdot C_{geometric} \cdot \eta_{optical} - P_{max}/(N \cdot A_{cell}) \qquad (6)$$

Combining equations (3) and (6), the cell temperature at maximum power point of the HCPV module is calculated as:

$$T_{c,Pmax} = T_{h\text{-}s} + R \cdot [\, DNI \cdot C_{geometric} \cdot \eta_{optical} - P_{max}/(N \cdot A_{cell})] \qquad (7)$$

As mentioned above, the measured heat-sink temperature of the module and the generated power density of the cell of the HCPV module are considered as average values due to the temperature distribution and the mismatch among solar cells of a HCPV module. Because of this, the cell temperature obtained with the equation (7) should be considered as the average cell temperature at maximum power point of the cells of a module connected to an inverter.

4. Analysis of results

In this section, the study of the results of the proposed method in the estimation of the cell temperature at maximum power point of the module connected to an inverter is presented.

Figure 4 shows the linear regression between the estimated and actual data. As can be seen there is an almost perfect fit between actual and estimated data: the slope is almost 1, the offset is 1.5 and the correlation coefficient is 0.99. From this analysis it can be concluded that the proposed method performs effectively in the estimation of the cell temperature of a HCPV module connected to an inverter.

Table 2 shows some statistical parameters that have also been analysed to study the proposed method in more detail: the mean bias error (MBE) and the relative and absolute root mean square error (RMSE). As can be seen the MBE is almost 0 % which indicates that the proposed method neither overestimates nor underestimates the cell temperature. Regarding the RMSE, a relative RMSE = 2.11 % and an absolute RMSE = 0.96 ºC have been found. This indicates the low deviation of the estimated data around the actual data and therefore the great degree of accuracy in the estimation of the cell temperature of the proposed method.

From the analysis of R^2, MBE and RMSE it can be concluded that the proposed method can be used for estimating the cell temperature of a HCPV module connected to an inverter with an adequate margin of error: R^2 = 0.99, MBE = -0.06 % and RMSE = 0.96 ºC. However, to study the proposed method in more detail, the absolute RMSE for each measured cell temperature level has also been checked and plotted in figure 5. As can be seen, the absolute RMSE shows a tendency to increase as cell temperature decreases and a tendency to decrease as the cell temperature increases. Nevertheless, it can be concluded that the method performs effectively for all cell temperature levels with an absolute RMSE ranging from 1.44 ºC to 0.55 ºC.

5. Cell temperature at maximum power point vs. cell temperature at open circuit

In this section the difference between the measured cell temperature at open circuit ($T_{c,oc}$) and the measured cell temperature at maximum power point ($T_{c,Pmax}$) is analysed. The cell temperature in a HCPV module depends on the air temperature, wind speed and direct normal irradiance. In particular, the cell temperature increases when air temperature increases and decreases with the wind speed [33]. However, modules under study have been measured at the same time in the same solar tracker and in the same position. This means that the influence of air temperature and wind speed is the same in both modules. Therefore, the difference between $T_{c,oc}$ and $T_{c,Pmax}$ is only given by the DNI because one module is at open circuit while the other is at maximum power point. Because of this, the difference between $T_{c,oc}$ and $T_{c,Pmax}$ is plotted versus the DNI. Figure 6 shows the average of the difference between both measured temperatures for different DNI levels. As can be seen, the difference between both temperatures increases with the DNI until a value around 875 W/m^2 with an approximate linear behaviour and with a difference ranging from 2.1 to 20.2 ºC. However, this difference remains almost constant at around 20.6 ºC for DNI values above 875 W/m^2.

This behaviour can be explained studying the difference between the heat power density at open circuit and the heat power density at maximum power point of the cells due to direct normal irradiance ($\Delta\rho_P$). The heat power density of a cell at open circuit of a HCPV module produced by the DNI can be expressed as:

$$\rho_{P,oc} = \rho_{P,recieved} = DNI \cdot C_{geometric} \cdot \eta_{optical} \quad (8)$$

So, the difference between the heat power density at open circuit and the heat power density at maximum power point of the cells due to DNI taking into account equations (4) and (8) can be written through:

$$\Delta\rho_P = \rho_{P,oc} - \rho_{P,Pmax} = \rho_{P,generated} = DNI \cdot C_{geometric} \cdot \eta_{optical} \cdot \eta_{cell} \quad (9)$$

Figure 7 shows the generated power density versus DNI of a cell, calculated using the equation (5). As can be seen, $\rho_{P,generated}$ increases linearly with DNI until a value around 875 W/m^2 while could be considered constant for DNI values above 875 W/m^2.This explains the behaviour of ΔT_c shown in figure 6.

It is also interesting to analyse why the generated power density of a cell in the HCPV module at maximum power point increases linearly with the DNI until a value around 875 W/m^2 and remains almost constant for higher values. It can be explained since the $\rho_{P,generated}$ increases with the DNI but also, because the efficiency of the cells plays an important role. Figure 8 shows the maximum, minimum and average efficiency of the HCPV module connected to the inverter at different DNI levels. As can be seen, the average efficiency of the module, and therefore the efficiency of the solar cells in the module, increases with the DNI and reaches a maximum at around 800 W/m^2 and then starts to decrease due to series resistance losses of the solar cells [34]. So that, although the $\rho_{P,generated}$ of the cell increases due to the DNI and the efficiency of the solar cells until around 875 W/m^2, the $\rho_{P,generated}$ keeps constant for DNI above 875 W/m^2 due to the increase of the DNI and the decrease of the solar cells efficiency.

6. Conclusions

A new method for estimating the cell temperature of a HCPV module has been introduced. The estimation of the operating cell temperature of a HCPV module or system plays an important role for its electrical characterization, energy prediction and thermal management. However, the existing methods for calculating the cell temperature of a HCPV module are only valid when the module is at open circuit. But, under actual operating conditions, HCPV modules are working at maximum power point because they are connected to an inverter. So, the new proposed method allows the estimation of the cell temperature of a HCPV module at maximum power point under actual operating conditions.

The experimental analysis conducted in section 5 shows the difference between the operating cell temperature of a HCPV module at maximum power point and cell temperature of a HCPV module at open circuit. As mentioned, a difference of up to 21 ºC between both temperatures has been found. This difference can be explained because when a HCPV module is connected to an inverter, the solar cells are generating power which is not transformed into heat. In this case, the difference between both temperatures varies from 2.1 to 20.6 ºC and follows the same behaviour as the generated power density of a cell of the module connected to the inverter. This justified the need to develop methods for estimating the cell temperature when a HCPV module is working under real operating conditions.

From the analysis of results it can be concluded that the proposed method performs effectively in the estimation of the operating cell temperature of a HCPV module connected to an inverter: $R^2 = 0.99$, MBE = -0.06 % and RMSE = 0.96 ºC. In addition, the absolute RMSE for each measured cell temperature level has also been analysed. An absolute RMSE ranging from 1.44 ºC to 0.55 ºC has been found.

As mentioned above, the proposed method calculates the average cell temperature at maximum power point of the cells of a module connected to an inverter. Therefore, this method is going to allow the average operating cell temperature of a HCPV system to be obtained. However, different considerations for estimating this temperature need to be taken into account. Like the mismatch among the cells in a module, there is an additional mismatch among the modules in a system. So, the generated power density calculated from the generated power of the system should be considered as an average of the electrical generated power density of a cell of the system. Because of this, to estimate the average cell temperature of the system it is also going to be necessary to determine the average heat-sink temperature of the system. Due to the temperature distribution among the cells in a module and among the modules in a system, measuring the heat-sink temperature of several HCPV modules of the system is necessary. The authors plan to study this in more detail and give the results found in future work.

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Figure captions

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

Figure 2. External quantum efficiency of the cells and transmittance of the lenses of the studied modules.

Figure 3. Experimental set-up used to carry out the study at the Centro de Estudios Avanzados en Energía y Medio Ambiente of the University of Jaén.

Figure 4. Linear regression analysis between actual and estimated data.

Figure 5. Absolute root mean square error (RMSE) versus actual cell temperature obtained for the proposed method.

Figure 6. Average of the difference between measured cell temperature at open circuit ($T_{c,oc}$) and measured cell temperature at maximum power point ($T_{c,Pmax}$).

Figure 7. Generated power density versus direct normal irradiance of a cell of the HCPV module connected to the inverter.

Figure 8. Maximum, minimum and average efficiency of the HCPV module connected to the inverter at different direct normal irradiance levels.