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Comparison Of Methods For Estimating The Solar Cell Temperature And Their Influence In The Calculation Of The Electrical Parameters In A HCPV Module

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Abstract. The electrical parameters of a multi-junction solar cell are influenced by its operating temperature. Hence, the estimation of the cell temperature of a HCPV module is critical for its electrical characterization. However, measuring the cell temperature of a HCPV module is a complex task due to its unique features. This paper calculates the cell temperature in a HCPV module by using a number of methods to address this important issue. We conducted a comparative study of three methods used to estimate the cell temperature of a HCPV module: the V_{oc}-I_{sc} method, the thermal resistance method and the lineal method. The results show that all of the studied methods can be used to estimate cell temperatures with an acceptable margin of error.

Keywords: high concentrator photovoltaic, cell temperature, mathematical methods, outdoor measurements
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INTRODUCTION

Nowadays, high concentrator photovoltaic (HCPV) modules are largely based on the use of multi-junction (MJ) solar cells. Similar to single-junction solar cells, the electrical parameters of MJ solar cells are influenced by their operating temperature [1, 2], hence the estimation of the cell temperature of a HCPV module is critical for its electrical characterization.

However, measuring the cell temperature of a HCPV module is a complex task since MJ solar cells are mounted on a substrate surrounded by different peripheral elements. In order to address this issue, different authors have proposed a range of methods for obtaining the cell temperature. These methods can be classified in three categories: methods based on heat-sink temperature, methods based on electrical parameters and methods based on atmospheric parameters [3].

In this paper, three different methods based on each of the categories referred to above for estimating the cell temperature are applied and compared. Also, an analysis of the influence of the errors in the cell temperature estimation in the calculation of the electrical parameters of a HCPV module is carried out.

EXPERIMENTAL CAMPAIGN

A HCPV module mounted on a two-axis solar tracker was under study at the Centre of Advanced Studies in Energy and Environment at the University of Jaen in Southern Spain (N 37º27'36'', W 03º28'12''). The electrical characteristics of the module and the main atmospheric parameters which affect its electrical performance were recorded. Also, a four-wire PT100 resistance thermometer placed close to the solar cell on a concentrator receiver (Fig.1-top) and a four-wire PT100 placed on the back of the module (Fig.1-bottom) to measure the solar cell temperature (T_c) and the heat-sink temperature ($T_{h\text{-}s}$) of the module were installed. All the parameters were recorded every five minutes from January 2011 to December 2013.

METHODS

In this section the V_{oc}-I_{sc} method based on electrical parameters, the thermal resistance method based on the heat-sink temperature and the lineal method based on atmospheric parameters are described [3].

The V_{oc}-I_{sc} Method

The proposed equation to obtain T_c is:

$$T_c = (\beta\, T_c^* + V_{oc} - V_{oc}^*)/((nk/q)N_s \ln(I_{sc}^*/I_{sc}) + \beta) \quad (1)$$

where T_c^* is the cell temperature at the reference conditions, β is the open circuit voltage temperature

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coefficient, V_{oc} is the open circuit voltage, V_{oc}^* is the open circuit voltage under the reference conditions, I_{sc} is the short-circuit current, I_{sc}^* is the short-circuit current under the reference conditions, n is the diode ideality factor of the multi-junction solar cells, k is the Boltzmann constant, q is the electron charge and Ns is the number of solar cells in series. All the parameters are obtained from outdoor measured data following the procedure described in [3]. It is important to note that the ratio I_{sc}^*/I_{sc} can also be estimated as DNI^*/DNI as defined in the IEC 60904-5 where DNI^* is the reference direct normal irradiance and DNI is direct normal irradiance.

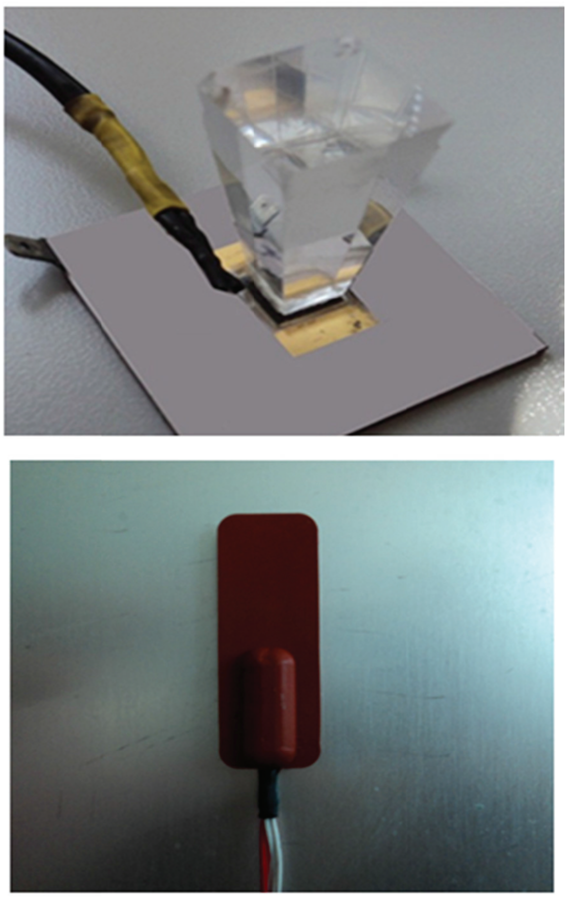

FIGURE 1. Location of the temperature sensors to measure the cell and heat-sink temperatures of the HCPV module.

The Thermal Resistance Method

The proposed equation to obtain T_c is:

$$T_c = T_{h\text{-}s} + DNI C_{geometric} \eta_{optical} R \quad (2)$$

where $C_{geometric}$ is the geometrical concentration, $\eta_{optical}$ is the optical efficiency and R is thermal resistance between the solar cells and the back surface of the module obtained following the procedure described in [3, 4]. It is important to note that this equation is only valid when the module is at open circuit since it does not take into account the generated power density of the solar cells when the module is at the maximum power point connected to an inverter [4].

The Lineal Method

The proposed equation to obtain T_c is:

$$T_c = T_{air} + aDNI + bW_s \quad (3)$$

where T_{air} is the air temperature and W_s is the wind speed. The a and b parameters are obtained from outdoor measured data following the procedure described in [3, 5].

COMPARATIVE STUDY

Analysis Of Results

In order to compare the methods mentioned above a range of statistical parameters have been studied. Figure 2 shows the linear regression analysis between the measured and estimated data. As can be seen the thermal resistance method gives the best results with a R^2 = 0.99. The V_{oc}-I_{sc} method yields similar results with R^2 = 0.98, while the Lineal method shows the poorest results with R^2 = 0.90. However, from this analysis it can be concluded that all the methods have a good performance in the estimation of cell temperature due to the fact that R^2 is equal or higher than 0.90.

Also, the absolute Root Mean Square Error (RMSE) between the measured and estimated data has been calculated, Table 1. Again the thermal resistance method shows the best behavior with a RMSE = 1.7ºC. The V_{oc}-I_{sc} method shows similar results with a RMSE = 2.0ºC while the Lineal method gives the poorest results with a RMSE = 4.3ºC. From this analysis it can also be concluded that all the methods perform effectively in the estimation of the cell temperature taking into account that the cells in a HCPV module are typically working in the range of 50-80ºC in 80% of the cases [3]

TABLE 1. Absolute root mean square error of the studied methods.

Method	RMSE (ºC)
V_{oc}-I_{sc}	2.0
Thermal resistance	1.7
Lineal	4.3

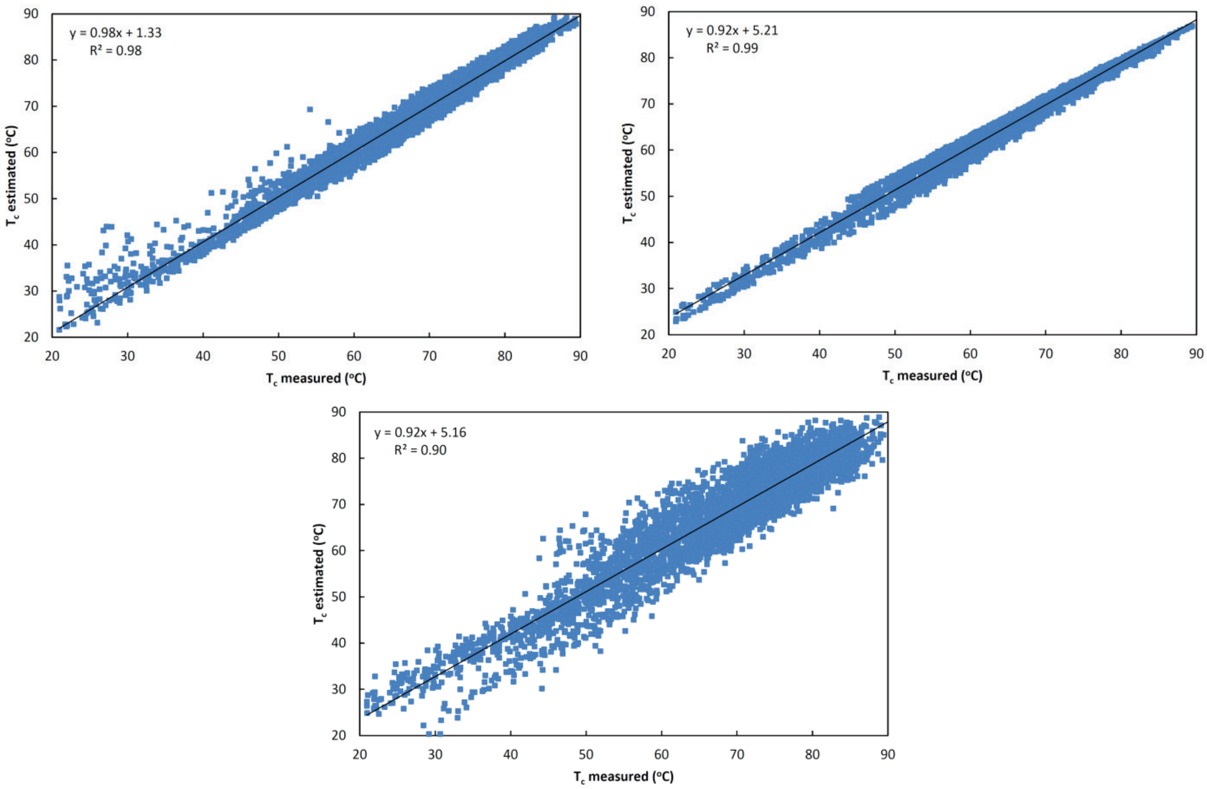

FIGURE 2. Linear regression analysis between measured and estimated data for the V_{oc}-I_{sc} method (top-left), the thermal resistance method (top-right) and the lineal method (bottom).

Influence On The Calculation Of The Electrical Parameters

The calculation of the cell temperature is an important issue in estimating the electrical parameters of a HCPV module. The temperature correction of an electrical parameter can be expressed as:

$$Z = Z^{*}(1 - T_{coeff}(T_c^{*} - T_c)) \tag{4}$$

where Z is the electrical parameter, Z^{*} is the electrical parameter under the reference conditions and T_{coeff} is its temperature coefficient. The deviation (ΔZ) between the electrical parameter calculated with the measured cell temperature and the electrical parameter calculated with the estimated cell temperature using the studied methods can be expressed as:

$$\Delta Z(\%) = (1 – Z(T_{c,measured})/ Z(T_{c,estimated}))100 \tag{5}$$

Combining equations (4) and (5), $\Delta Z(\%)$ can be expressed as:

$$\Delta Z (\%) = [(1 - T_{coeff}(T_c^{*} - T_{c,measured}))/ (1 - T_{coeff}(T_c^{*} - T_{c,estimated}))]100 \tag{6}$$

To estimate ΔZ (%) by using equation (6), it is necessary to know the values of T_{coeff} for each electrical parameter. The temperature dependence of several HCPV modules has been studied in [6]. Based on this study, the temperature coefficients of short-circuit current, open circuit voltage and fill factor (FF) shown in table 2 have been selected as representative values of a HCPV module.

Table 2 shows the maximum, minimum and average deviation of I_{sc}, V_{oc} and FF. The thermal resistance method shows the best results with a deviation ranging from 0.48% to -0.68%, 0.95% to -0.66% and 0.85% to -0.59% for I_{sc}, V_{oc} and FF respectively. The V_{oc}-I_{sc} method shows the second best results with a deviation ranging from 0.59% to -1.96%, 2.78% to -0.81% and 2.48% to -0.73% for I_{sc}, V_{oc} and FF respectively. The lineal method again shows the poorest results with a deviation ranging from 1.73% to -2.29%, 3.07% to -2.47% and 2.75% to -2.19% for I_{sc}, V_{oc} and FF respectively. As can also be seen, the average deviation of all the methods studied here for all the electrical parameters is almost 0%. This indicates that all the methods can be used to estimate the cell temperature of a HCPV module with a satisfactory degree of accuracy in order to estimate the electrical parameters of a HCPV module.

TABLE 2. Temperature coefficients and deviation of the errors in the calculation (maximum, minimum and average) of the electrical parameters of a HCPV module.

Method	I_{sc} (T_{coeff} = 0.12 %/K)			V_{oc} (T_{coeff} = -0.18 %/K)			FF (T_{coeff} = -0.16 %/K)		
	Maximum (%)	Minimum (%)	Average (%)	Maximum (%)	Minimum (%)	Average (%)	Maximum (%)	Minimum (%)	Average (%)
V_{oc}-I_{sc}	0.59	-1.96	-0.01	2.78	-0.81	0.01	2.48	-0.73	0.01
Thermal resistance	0.48	-0.68	0.01	0.95	-0.66	0.00	0.85	-0.59	0.00
Lineal	1.72	-2.29	0.04	3.07	-2.47	-0.06	2.75	-2.19	-0.05

CONCLUSIONS

In this paper the Voc-Isc method based on electrical parameters, the thermal resistance method based on the heat-sink temperature and the lineal method based on atmospheric parameters for estimating the cell temperature are described and examined.

In order to compare and study the results of these methods, different statistical analyses were conducted. Based on these analyses, it can be concluded that the thermal resistance method shows the best results with a R^2 = 0.99 and an absolute RMSE = 1.70 ºC. The V_{oc}-I_{sc} method shows similar results, with a R^2 = 0.98 and an absolute RMSE = 2.00 ºC. The Lineal method provides the poorest results, with a R^2 = 0.90 and an absolute RMSE = 4.30 ºC.

In addition, a study ofthe influence of the errors in the estimation of the cell temperature in the calculation of the electrical parameters of a HCPV module was carried out. In particular, the maximum, minimum and average deviation between the short-circuit current, open circuit voltage and fill factor calculated with the measured cell temperature and the estimated cell temperature using the studied methods was analysed. Based on this analysis, it can be concluded that the thermal method shows the best results, with a maximum deviation ranging from 0.95% to -0.66%, the V_{oc}-I_{sc} method shows the second best results, with a maximum deviation ranging from 2.78% to -0.81% and the Lineal method presents the poorest results, with a maximum deviation ranging from 3.07% to -2.47%.

It is important to note that, despite the fact that some methods show a better performance than others, all of them could be used for the estimation of the cell temperature with an acceptable margin of error. The rationale behind this is the fact that all of them have an R^2 value equal to or greater than 0.90, an absolute RMSE equal to or lower than 4.30 ºC (considered an acceptable margin of error, taking into account that the cells in a HCPV module typically work in the range 50-80 ºC in approximately 80% of the cases) and an average deviation in the estimation of the electrical parameters of 0%.

It can also be concluded that the V_{oc}-I_{sc} method and the thermal resistance method based on direct measurements on a HCPV module give better results than the lineal method based on atmospheric parameters. However, it is important to note that the methods based on atmospheric parameters have the advantage of allowing the estimation of the cell temperature of a HCPV module for a specific location without directly measuring the module while the methods based on direct measures on a HCPV module are more suitable for field performance analysis.

REFERENCES

1. Eduardo F. Fernández, G. Siefer, F. Almonacid, A. J. García-Loureiro, P. Pérez-Higueras, *A two subcell equivalent solar model for III-V triple junction solar cells under spectrum and temperature variations*, Solar Energy, 2013, 92, pp. 221-229.
2. Eduardo F. Fernández, G. Siefer, M. Schachtner, A. J. García-Loureiro, P. Pérez-Higueras, *Temperature coefficients of monolithic III-V triple-junction solar cells under different spectra and irradiance levels*, AIP conference proceedings, 2012, 1477, pp. 189-193.
3. Eduardo F. Fernández, F. Almonacid, P. Rodrigo, P. Pérez-Higueras, *Calculation of the cell temperature of a high concentrator photovoltaic (HCPV) module: A study and comparison of different methods,* Solar Energy Materials and Solar Cells, 2014, 121, pp. 144-151.
4. Eduardo F. Fernández, P. Rodrigo, F. Almonacid, P. Pérez-Higueras, *A method for estimating cell temperature at the maximum power point of a HCPV module under actual operating conditions,* Solar Energy Materials and Solar Cells, 2014, 124, pp. 159-165.
5. F. Almonacid, P. Pérez-Higueras, Eduardo F. Fernández, P. Rodrigo, *Relation between the cell temperature of a HCPV module and atmospheric parameters,* Solar Energy Materials and Solar Cells, 2012, 105, pp. 322-327.
6. G. Peharz, J. P. Ferrer Rodríguez, G. Siefer, A. W. Bett, *Investigations on the temperature dependence of CPV modules equipped with triple-junction solar cells*, Progress in Photovoltaics: Research and Applications, 2011, 19 (1), pp. 54-60.