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Spectrally corrected direct normal irradiance based on artificial neural networks for high concentrator photovoltaic applications

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A B S T R A C T

The electrical characterization of a HCPV (high concentrator photovoltaic) module or system is key issue for systems design and energy prediction. The electrical modelling of an HCPV module shows a significantly greater level of complexity than conventional PV (photovoltaic) technology due to the use of multi-junction solar cells and optical devices. An interesting approach for the modelling of an HCPV module is based on the premise that the electrical parameters of an HCPV module can be obtained from the spectrally corrected direct normal irradiance and the cell temperature. The advantage of this approach is that the spectral effects of an HCPV device are quantified by adjusting only the incident direct normal irradiance. The aim of this paper is to introduce a new method based on artificial neural networks to spectrally correct the direct normal irradiance for the electrical characterization of an HCPV module. The method takes into account the main atmospheric parameters that influence the performance of an HCPV module: air mass, aerosol optical depth and precipitable water. Results show that the proposed method accurately predicts the spectrally corrected direct normal irradiance with a RMSE (root mean square error) of 2.92% and a MBE (mean bias error) of 0%.

1. Introduction

Modelling the electrical performance of a photovoltaic device is crucial for systems design and energy prediction. Nowadays, HCPV (high concentrator photovoltaic) technology is based on the use of MJ (multi-junction) solar cells and optical devices to concentrate the light on the MJ solar cell surface. Usually, the optical devices consist of a primary optical element and a secondary optical element. The primary optical device, usually a Fresnel lens, collects direct sunrays while the secondary optical device receives the light from the primary one to homogenize light and improve the angular acceptance to focus the light on the solar cell [1–3]. In an MJ solar cell each junction responds at a particular band of the incident spectral distribution [4]. In addition, the optical elements modify the spectral distribution of the incident solar irradiance [5–7]. Hence, the electrical modelling of HCPV modules and systems shows a significantly greater level of complexity than conventional PV technology [8].

Several authors have proposed different models and procedures for the electrical characterization of HCPV modules [9–17]. Most of these models are focused on the estimation of the maximum power since it discloses the energy yield, however other important parameters such as short-circuit current, open circuit voltage, current at maximum power point and voltage at maximum power point are not addressed [9–15]. Other models recently proposed allow other electrical parameters than maximum power of an HCPV module to be estimated [16,17]. However, these models are difficult to apply since they usually required detailed information about the materials and characteristics of the module and need complex and expensive instruments to be applied.

A different approach for the modelling of an HCPV module or system is pointed out in Refs. [18,19]. This approach is based on the premise that the electrical parameters (short-circuit current, open circuit voltage, current at maximum power point, voltage at maximum power point and maximum power) can be obtained from the spectrally corrected direct normal irradiance and the cell temperature [8,20]. The advantage of this approach is that the spectral effects are quantified by adjusting only the incident direct normal irradiance. The method for the spectral correction of the direct normal irradiance proposed in Ref. [18] is based on the use of

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isotype solar cells. However, although isotype solar cells have demonstrated to be a simple and excellent tool for quantifying the spectral effects, the use of these devices is difficult to apply in remote sites for long-term analysis and is more adequate for short-term and power rating analysis [10,18,21]. The method proposed in Ref. [19] is based on a spectral correction of the direct normal irradiance by the use of the so-called "air mass function". This method has the advantage that is easy to apply since the air mass can be easily obtained from the sun position [22]. However, the spectral distribution of the solar irradiance is also influenced by other atmospheric parameters such as aerosol optical depth and precipitable water [23,24]. The influence of these parameters on the air mass function has been studied in Ref. [25] and a far from negligible influence has been found. This means that a function to spectrally correct the direct normal irradiance should take into account these parameters to accurately quantify the spectral impacts on an HCPV module.

The aim of this paper is to introduce a new method to spectrally correct the direct normal irradiance for the electrical characterization of an HCPV module. The method is based on a function that takes into account the main atmospheric parameters that influence the performance of an HCPV module: air mass, aerosol optical depth and precipitable water. The proposed methodology has the advantage that is based on atmospheric parameters, so is valid for long-term analysis at any location if these data are available. Due to the complexity of finding an analytical relationship among these parameters, an artificial neural network based-model has been used to adjust this function. Also, a comparative study between the proposed function and the air mass function for estimating the spectrally corrected direct normal irradiance is conducted.

2. Spectrally corrected direct normal irradiance

Photovoltaic devices do not respond to the all the wavelengths of the solar spectrum. Taking this into account, DNI_c (spectrally corrected direct normal irradiance) represents the portion of the incident spectrum that an HCPV module is able to convert into electricity.

The short-circuit current density of each junction of an MJ solar of an HCPV module can be expressed as [26]:

$$J_{sc,i} = C_{geo} \int E_b(\lambda)\eta(\lambda)\mathrm{SR}_i(\lambda)\mathrm{d}\lambda \tag{1}$$

where the index i represents the junction considered, λ is the wavelength, $\mathrm{SR}_i(\lambda)$ is the spectral response of the i-junction, $E_b(\lambda)$ is the spectral distribution of the direct normal irradiance and $\eta(\lambda)$ is the optical efficiency of the HCPV module. C_{geo} is the geometrical concentration of the HCPV module defined as:

$$C_{geo} = \frac{A_{lens}}{A_{cell}} \tag{2}$$

where A_{lens} is the area of the primary optics and A_{cell} is the area of the cells.

Due to the fact that the junctions of an MJ solar cell are interconnected in series, the short-circuit current density of an HCPV module is given by Ref. [27]:

$$J_{sc} = \min\left(J_{sc,i}\right) \tag{3}$$

From Equations (1)–(3), the spectrally corrected direct normal irradiance of an HCPV module can be expressed as [18]:

$$\begin{aligned}\mathrm{DNI}_c &= \frac{\min\left(\int E_b(\lambda)\eta(\lambda)\mathrm{SR}_i(\lambda)\mathrm{d}\lambda\right)}{\min\left(\int E_{b,\mathrm{ref}}(\lambda)\eta(\lambda)\mathrm{SR}_i(\lambda)\mathrm{d}\lambda\right)}\int E_{b,\mathrm{ref}}(\lambda)\mathrm{d}\lambda \\ &= \frac{A_{cell}I_{sc}}{A_{cell}I^*_{sc}}\mathrm{DNI}^* = \frac{I_{sc}}{I^*_{sc}}\mathrm{DNI}^*\end{aligned} \tag{4}$$

where $E_{b,\mathrm{ref}}(\lambda)$ is the reference spectrum AM1.5d ASTM G-173-03 provided by the ASTM (American Society of Testing and Materials) at which MJ solar cells and HCPV modules are rated [28], I_{sc} is the short-circuit current ($I_{sc} = A_{cell}J_{sc}$) of the HCPV module at operating conditions, I^*_{sc} is short circuit current of the HCPV module at the reference conditions and DNI^* is the integral of the reference spectrum or reference direct normal irradiance.

Dividing by the direct normal irradiance, Equation (4) can be rewritten as:

$$\frac{\mathrm{DNI}_c}{\mathrm{DNI}} = \frac{I_{sc}}{I^*_{sc}}\frac{\mathrm{DNI}^*}{\mathrm{DNI}} = f_s \tag{5}$$

where f_s is defined as the spectral correction function.

Finally, the spectrally corrected direct normal irradiance is expressed as:

$$\mathrm{DNI}_c = \mathrm{DNI}f_s \tag{6}$$

The spectral correction function proposed by the Sandia National Laboratories in the Performance Array Performance Model for the spectral correction of the direct normal irradiance is [19]:

$$f_s = f_s(\mathrm{AM}) = a_0 + a_1\mathrm{AM} + a_2\mathrm{AM}^2 + a_3\mathrm{AM}^3 + a_4\mathrm{AM}^4 \tag{7}$$

where AM is the air mass. As can be seen, in this case the spectral correction function depends only on the air mass. The coefficients of the air mass function are empirically obtained from outdoor monitored data plotting the measured f_s using Equation (5) against AM and following the procedure described in Refs. [29–32].

Equation (7) quantifies the spectral influence on the performance of an HCPV module through the air mass. However, although the air mass is the main reason for spectral changes [14], there are other atmospheric parameters that affect the spectral distribution of the incident spectrum. As is signalled in Refs. [16,33], AOD (aerosol optical depth) and PW (precipitable water) have an important influence on the performance of an HCPV module. Because of this, the spectral correction function should take into account these parameters to accurately quantify the spectral effects on an HCPV module.

3. Spectral correction function based on an artificial neural network

As mentioned above, the spectral distribution of the incident irradiance and the performance of an HCPV module are mainly influenced by air mass, aerosol optical depth and precipitable water. So, the spectral correction function to correct the direct normal irradiance could be defined as a function of these atmospheric parameters:

$$f_s = f_s(\mathrm{AM}, \mathrm{AOD}, \mathrm{PW}) \tag{8}$$

However, it is difficult to formulate an analytical equation that provides the relationship among these parameters. ANN (Artificial neural networks) have proven to be effective in the solutions to complex problems applied to photovoltaic technology [12,34–40]. Therefore, the authors have developed a method based on the use