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# High concentrator photovoltaic module simulation by neuronal networks using spectrally corrected direct normal irradiance and cell temperature

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ABSTRACT

The electrical modelling of HCPV (high concentrator photovoltaic) modules is a key issue for systems design and energy prediction. However, the electrical modelling of HCPV modules shows a significantly level of complexity than conventional photovoltaic technology because of the use of multi-junction solar cells and optical devices. In this paper, a method for the simulation of the I–V curves of a HCPV module at any operating condition is introduced. The method is based on three different ANN (artificial neural networks)-based models: one to spectrally correct the direct normal irradiance, one to predict the cell temperature and one to generate the I–V curve of the HCPV module. The method has the advantage that is fully based on atmospheric parameter and outdoor measurements. The analysis of results shows that the method accurately predicts the I–V curve of a HCPV module for a wide range of atmospheric operating conditions with a RMSE (root mean square error) ranging from 0.19% to 1.66% and a MBE (mean bias error) ranging from −0.38% to 0.40%.



## 1. Introduction

7HCPV (high concentrator photovoltaic) technology uses cheap optical devices to decrease the solar cell area with the aim of reducing the cost of electricity [1]. HCPV technology is widely based on the use of high efficiency III–V MJ (multi-junction) solar cells in which each junction (usually three) responds to a particular band of the spectrum in order to increase the efficiency of the device [2]. The optical devices usually consist of a primary optical element (usually a Fresnel lens) which concentrates the light and a secondary optical element that receives the light from the primary ones to homogenize light and improve the angular acceptance angle [3]. A HCPV module is made up of several MJ solar cells and optical devices, and the rest of the components to generate electricity and dissipate the heat produced on the solar cell surface. MJ solar cells and HCPV modules have already reached high efficiencies which are expected to continue growing next few years [4–8]. Because of this, HCPV technology could play an important role in the energy generation market within next few years with a cumulative installed capacity that could pass from 358 MWp in 2014 to more than 1 GWp in 2020 [9].

Bearing this in mind, the electrical modelling of HCPV modules is crucial for systems design and energy prediction, and therefore to promote the market expansion of HCPV technology [10–14]. However, due to its special features, the electrical modelling of HCPV modules shows a significantly great level of complexity than conventional photovoltaic technology. Because of this, in recent years, the scientific community has devoted considerable efforts in developing models that reproduce the electrical performance of HCPV modules, for instance, [15–21]. These models are mainly focused in the estimation of the maximum power since allows the energy yield to be estimated and other crucial parameters for the electrical characterization of HCPV modules such as short-circuit current, open-circuit voltage, maximum power current and voltage are not addressed. The models proposed in Refs. [19,20] allow other parameters than the maximum power to be extracted since the maximum power is obtained by solving the complete I–V curve of the module. These methods offer a valuable tool for the electrical characterization of HCPV modules since a detailed

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modelling of each of the components of modules are taken into account. In both methods the spectral distribution of the incident direct normal solar irradiance is obtained with the SMARTS (simple model of the atmospheric radiative transfer of sunshine) (SMARTS [22]). Once the spectral distribution is obtained, the incident spectrum that strikes the solar cell surface is obtained taking into account the optical properties of the modules. After that, the I–V curve of each MJ solar cell is obtained from the external quantum efficiency of each junction and from different semiconductor properties of the solar cells. Finally, the I–V curves of each cell are associated in order to obtain the complete I–V curve of the HCPV module. One possible disadvantage of these methods is the fact that require detailed information of the materials of the modules which are not always available and advanced knowledge of semiconductor physics, optics and different specific software. In any case, the estimation of the I–V curve of a HCPV module and its validation with long-term measurements in outdoors has not been addressed yet.

The simulation of the I–V curve of a module is a key factor for the electrical characterization and design of systems and power plants. The modelling of the I–V curve of a module allows the association in series and in parallel of modules to be done and therefore the simulation of the I–V curve of the generator under the time-varying atmospheric parameters. This is important for energy prediction issues, but also to estimate the current and voltage at a desire point of the I–V curve of the generator. This is crucial for the design of the electrical requirements and protections of a system or power plant, and also because the generator works in different regions of its I–V curve depending on the regulation and control devices used in each installation. Besides, the simulation of the I–V curve allows the maximum power current and voltage of the generator to be obtained. This is valuable information in choosing and sizing the inverter of a grid-connected system depending on its module electrical configuration and the solar resource and atmospheric parameters of each specific location. Furthermore, in an off-grid-connected system, the battery voltage or charge regulator may determines the working point of the generator and therefore the complete I–V curve is fundamental since the generator works in different points of its I–V curve.

The main reason of the complexity of the electrical modelling of HCPV modules lies in the use of MJ solar cells and optical devices. The internal series connection of several cells with different band gap energies and the use of optical devices which modify the spectral distribution of the solar irradiance make these devices more sensible to the incident spectrum [23,24]. An interesting approach for the electrical characterization of HCPV modules is pointed out in Refs. [25,26]. This approach is based on the idea that the electrical characteristics of a HCPV module can be estimated from the spectrally corrected $DNI_c$ (direct normal irradiance) and the cell temperature ($T_{cell}$). This is interesting since the spectral influence of HCPV modules is quantified by adjusting only the DNI (direct normal irradiance). In [25] a procedure to obtain the maximum power as a function of $DNI_c$ and $T_{cell}$ is introduced. The procedure to correct DNI is based on measures gathered with isotype solar cells, so that is more adequate for short-term and power rating analysis. In [26] a method based on a set of analytical equations to obtain the short-circuit current, open-circuit voltage, maximum power current, maximum power voltage and maximum power as a function of $DNI_c$ and $T_{cell}$ is described. This method corrects DNI by the use of the so-called "air mass function". Because of this, it has the advantage that can be used in remote sites for long-term analysis since the air mass can be easily obtained from the sun position [27]. This method is widely used in conventional PV technology and has also demonstrated good results in the electrical characterization of HCPV devices [8,28].

Based on the approach commented above, in this work we introduce a method based on ANN (artificial neural networks) and atmospheric parameters for obtaining the I–V curve of a HCPV module as a function of $DNI_c$ and $T_{cell}$. There are several examples in the application of artificial networks in the generation of the I–V curve of conventional photovoltaic modules [29–35]. The use of ANNs is appropriate due to their ability in solving complex problems related with photovoltaics and their good results concerning the electrical characterization of concentrator photovoltaic technology [36–39]. Furthermore, the method is fully based on atmospheric parameter and outdoor measurements. The use of atmospheric parameters has the advantage that allows the electrical characterization at a desired location if the atmospheric parameters are available to be done. Also, the method has the advantage that not required detailed information about the materials and characteristics of the module [21].

## 2. Experimental set-up

To conduct this study, a HCPV module was monitored from July to December 2013 at the Centre of Advanced Studies in Energy and Environment (CEAEMA) at the University of Jaen in Southern Spain (N 37°27′36″, W 03°28′12″). The main characteristics of the module are shown in Table 1. The module was mounted on a high accuracy two-axis solar tracker designed by the BSQ Company placed on the roof of the research centre (Fig. 1-left). The electrical characteristics of the HCPV module were measured by the use of a four-wire electronic load (PVPM 1000C40) located in the laboratory. The cell temperature was measured with a four-wire PT100 located close to the solar cell. This thermometer was located in a receiver between the centre and the border of the module, so that the measured temperatures should be considered as the average temperature of a receiver due to the temperature distribution of a HCPV module [40]. This approach has been previously used and has been considered as an adequate procedure for estimating the cell temperature of a HCPV module and for its electrical characterization [41]. In order to record the cell temperature, the temperature sensor was connected to a data logger (Agilent 34970A) located in the laboratory. In addition, an atmospheric station (MTD 3000 from Geonica Company) placed on the roof of the centre linked via internet to a Personal Computer placed in the laboratory (Fig. 1-right) recorded the main atmospheric parameters: direct normal irradiance, air temperature, wind speed or humidity. All the parameters were recorded daily every 5 min. In addition, the daily average values of aerosol optical depth at 550 nm and precipitable water not provided by the atmospheric station were obtained from MODIS Daily Level-3 data source [42].

## 3. Method description

The process followed to predict the I–V curve of a HCPV module based on artificial neural networks is described in Fig. 2. As can be seen, the proposed method is comprised of three blocks. The modelling approaches and input required parameters are described

**Table 1**
Characteristics of the high concentrator photovoltaic module used in the study.

| | |
|---|---|
| Geometric concentration | 700 |
| 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 |