New software tool to characterize photovoltaic modules from commercial equipment

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Abstract

A software platform has been developed in order to unify the different measurements obtained from different manufacturers in the photovoltaic system laboratory of the University of Malaga, Spain. These measurements include the current-voltage curve of PV modules and several meteorological parameters such as global and direct irradiance, temperature and spectral distribution of solar irradiance. The measurements are performed in an automated way by a stand-alone application that is able to communicate with a pair of multimeters and a bipolar power supply that are controlled in order to obtain the current–voltage pairs. In addition, several magnitudes, that can be configured by the user, such as irradiance, module temperature or wind speed, are incorporated to register the conditions of each measurement. Moreover, it is possible to attach to each curve the spectral distribution of the solar radiation at each moment. Independently of the source of the information, all these measurements are stored in a uniform relational database. These data can be accessed through a public web site that can generate several graphics from the data.

Keywords: measurement system; photovoltaic modules; predicting cell temperature; predicting spectral distribution of solar irradiance

1. Introduction

In a typical photovoltaic laboratory it is possible to find several instruments from different manufacturers used to measure the current–voltage curve of a photovoltaic module and other meteorological parameters. As each system has its own protocol and software, it is very difficult to synchronize all of them in order to generate a consistent set of measurements. In the photovoltaic laboratory of the University of Málaga (Spain), we have developed our own software platform in order to unify the measurement process. The measurements are performed in an automated way by a stand–alone application able to communicate with a pair of multimeters and a bipolar power supply that are controlled in order to obtain the current–voltage characteristic curves of each module. In addition, several magnitudes, that can be configured by the user, such as irradiance, module temperature or wind speed, are incorporated to register the conditions of each measurement. Moreover, as a new spectrorradiometer has recently bought, it is possible to attach to each I-V curve the spectral distribution of the solar radiation at the same time. Independently of the source of the information, all these measurements are stored in a uniform relational database. On the other hand, these data could be accessed through a public web site that can show to the user several graphics generated from the data that could be very useful for different research projects. In the last version of this software, several enhancements have been added, including several methods to forecast the module temperature from other meteorological magnitudes and an accurate tool to synthesize the solar spectrum from others values.

2. Methodology and models

The study of the behaviour of the different elements that are part of a photovoltaic plant is a key factor to study the feasibility of the installation of this type of systems. The engineers who are responsible for the design and dimensioning of solar power plants need to have tools that allow them to predict the behaviour of photovoltaic modules under different conditions. Basically, the most influential of all these conditions is the irradiance, but the temperature of the module and the spectral composition of the incident radiation can be considered as variables of second order and third order in the output of photovoltaic modules. The manufacturers of solar modules specify the value of the electrical parameters under the STC conditions (standard test conditions) in the specifications: global irradiance in the module plane of 1000 W/m^2, module temperature equal to 25 °C and a specific spectral distribution AM 1.5, which is defined in the international standard IEC

60904-3 [1]. However, it is necessary to have models that allow us to obtain these electrical parameters under other conditions than those mentioned STC.

On the other hand, the performance of certain recently implemented technologies, such as thin-film modules, has a greater dependence on the solar spectrum than conventional technologies such as monocrystalline silicon and multicrystalline silicon. In short, for a precise characterization of the behaviour of photovoltaic modules, the traditional models fall short and therefore we are looking for new models that take into account the spectrum.

Models for the prediction of the operating temperature of the photovoltaic module: There are mathematical models that allow estimating the actual operating temperature of the photovoltaic cells from the current value of a series of meteorological or electrical variables of the photovoltaic module. Each of these models requires certain parameters for its use, the value of which depends on the technology of the photovoltaic module with which they are working. The temperature prediction models of the module can be instantaneous (using instantaneous values of the variables) or hourly (using integrated hourly values of these variables).

The models of instantaneous temperature prediction that are currently implemented in the system are the NOCT model, defined by IEC 61215 [2] for crystalline silicon modules and by IEC 61646 [3] standard for thin film modules, Risser [4], Servant, King, Ross, Mattei, NOCT-1p and NOCT-2p, described in [5], and Electric_Isc and Electric_G [6]. The hourly temperature prediction models are described in [5,7].

Model for the prediction of solar spectra: The performance of some PV technologies, such as thin-film modules, has a greater dependence on the solar spectrum than conventional technologies such as monocrystalline silicon and multicrystalline silicon. The developed system has integrated the model proposed in [8] to predict the spectral distribution of solar radiation.

3. Description of the system

The hardware and software architecture of the system is presented in this section. The proposed system is not only able to measure the current-voltage curve of several photovoltaic modules and the external conditions at the time of measurement (including the solar spectrum), but also incorporates a calculation engine that implements several prediction models. First, the user is able to introduce a model to estimate the module temperature based the measured values of some meteorological magnitudes (some of these models have been previously incorporated). Second, a previously published model [8] focused to forecast the solar spectrum based only on meteorological data and astronomical relationships is also implemented.

This software is divided into four subsystems: configuration interface (S1), measurement daemon (S2), integration and model engine (S3), and finally, web visualization interface (S4). In addition, a database is used to interchange data between the subsystems throughout this database. Each of these subsystems can be described in terms of smaller parts as can be seen in Figure **1**.

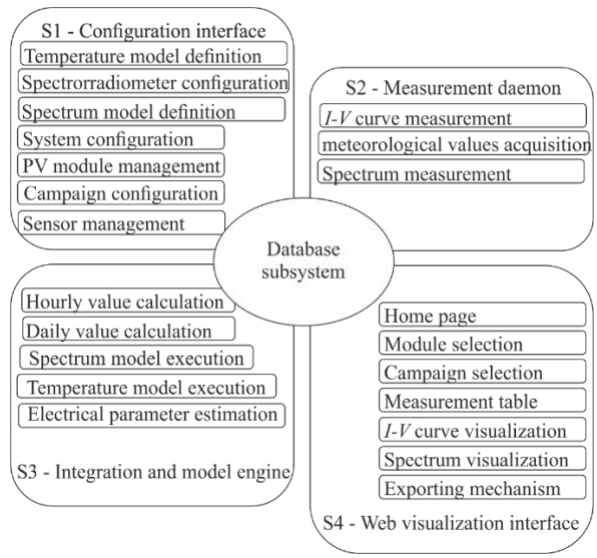


Figure 1. Components of the software

Hardware architecture of the system

Prior to a description of the software subsystems, the global hardware architecture will be depicted general scheme of the architecture of the system from the hardware point of view is shown in Figure **2**.

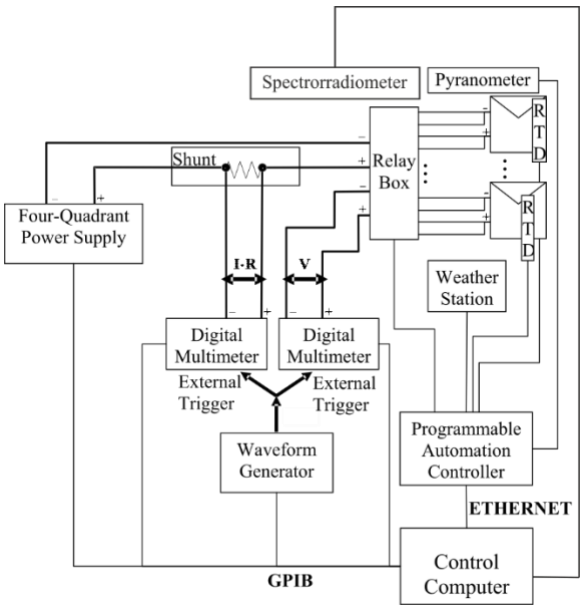


Figure 2. Hardware architecture

On the one hand, the measurement of the I–V curve is performed reading the current throughout the module when a bipolar power supply bias the voltage across its terminals from the short circuit to the open circuit. The current voltage pairs are acquired by two multimeters (actually the current values are measured using a shunt resistor) controlled by the application using the GPIB protocol. Both of them are synchronized by a square signal (from a wave generator), which activates the external trigger input of each multimeter at the same time, improving the accuracy of the I–V pairs [9]. On the other hand, the external conditions are also acquired at the time of measurement: the module temperature of each specimen is measured using a sensor coupled to its backside and a reference cell or a pyranometer captures the incident irradiance. These magnitudes and several additional ones (air temperature, wind speed and direction, atmospheric pressure, etc.) are sensed by several transducers connected to a programmable automation controller whose registers are accessible at real-time through the protocol OPC DA [10] over Ethernet. This equipment is also used to select the photovoltaic module to be measured among eights specimens using a relay box that multiplexes several electric channels into a unique input to the measurement system. Finally, the spectral distribution of the solar irradiance is registered with the help of a grating spectrorradiometer connected to the control computer using a RS 485 bus under which a proprietary protocol serves the spectrum each time it is requested.

Configuration interface

Stand-alone software can be used to set the global parameters of the system (such as the communication port of each electronic device), to register the photovoltaic modules to be measured, and to configure the voltage sweep for each specimen to measure its I–V curve. In addition, this application allows the user to start or finish a campaign of measurements or to adjust the required parameters and formula of the prediction models. After executing the application, the main window (see Figure **3**) shows an overview of the current state of each channel of the relay box next to a menu of different options, where each button provides access to each window: system configuration, photovoltaic module management, campaign management, sensor configuration, spectrorradiometer configuration, temperature model definition window, and spectrum model definition window.

This screen (see Figure **3**) allows the configuration of the parameters relative to the photovoltaic module to be measured and the limits and number of points of the voltage sweep, that could be performed in two stages: a fast ramp with a few points to capture the part of the curve with small slope (before the knee of the curve), and a slow ramp with more points to acquire the maximum power point and the open-circuit voltage with more accuracy.

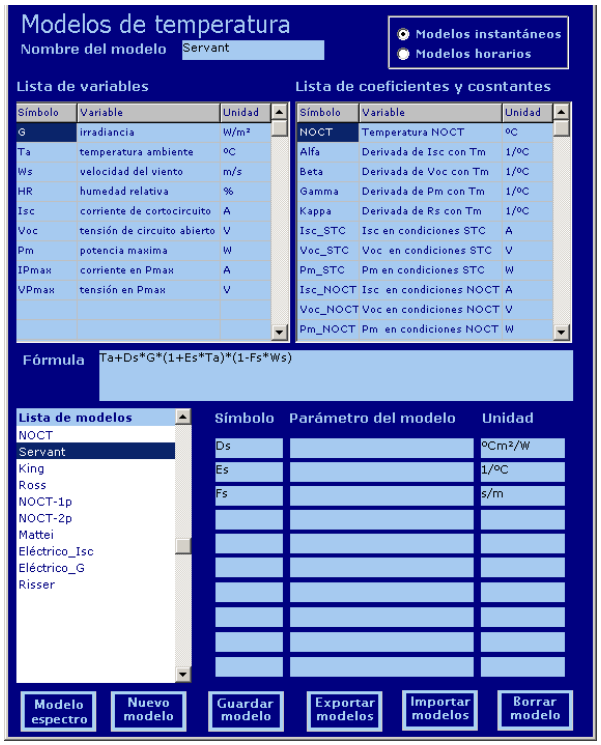


Figure 3. Defining and configuring a new temperature model

Measurement daemon

The measurement daemon is running in the background and at regular intervals of time, an execution thread is thrown to

measure each photovoltaic device connected to the relay box and associated to an active campaign of measurements. The power supply is commanded to perform the voltage sweep while the current and voltage values are stored in the internal memory of both multimeters. In addition, the solar spectrum and other meteorological measurements are retrieved from the spectrorradiometer and the programmable automation controller respectively. The measured I–V curve, the recorded meteorological variables, and the incident solar spectrum are registered in the database only if some filters about the external conditions are satisfied in order to ensure the stability of those conditions during the voltage sweep.

Integration and model engine

Each time a new record is inserted into its respective table of measurements corresponding to a campaign over a specific photovoltaic module, the integration and model engine is activated to process that information. First, the main electrical parameters of the I–V curve are estimated (such as the short-circuit current, the open-circuit voltage and the maximum power). Then, for each instantaneous measured value, an accumulated variable is updated in order to compute its hourly and daily integral (or averaged) value.

The system allows defining a series of models of this type as well as the assignment of the values of the parameters for each module registered in the system. To enter a model in the system it is only necessary to write its equation. So, for example, the Ross model for instantaneous values of temperature is:

$$T_m = T_{amb} + kG \tag{1}$$

where T_m is the temperature of the module, T_{amb} is the ambient temperature, G is the incident irradiance and k is the Ross coefficient that depend, among the other factors, on the technology of the module, its shape and size, encapsulation, assembly and environmental conditions.

The equation of hourly NOCT-2p model is:

$$T_{m-h} = T_{amb-h} + b_h \left[\frac{H}{800\,\mathrm{Wh/m^2}} \left(NOCT - 20\,^\circ\mathrm{C} \right) \right] + c_h \left(W_h - 1\,\mathrm{m/s} \right) \tag{2}$$

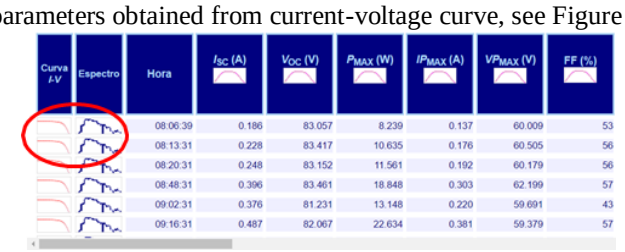
where T_{m-h} is the average temperature of the module in one hour, T_{amb-h} is the hourly mean of the ambient temperature, H is the hourly irradiation received by the module, W_h is the hourly average of the wind speed and b_h and c_h are parameters whose values depend on the technology of the module. The values of all the parameters of all the implemented models can be seen in [5].

If for a photovoltaic module its temperature is calculated using different prediction models, and it is also indicated to the system a temperature sensor to be considered as the real temperature of the module (T_{m-real}), it is possible to calculate the discrepancy between the temperature predicted by these models and the measured temperature using different metrics. This option allows us to access the measurement of the error of each temperature model. The selected metrics used for evaluating the models are described in [5].

Finally, if the solar spectrum model is activated, an estimation of the spectral distribution is forecasted using as inputs to the model the measured meteorological variables and the value of the solar angles at the time of measurement. This estimation is stored in the database next to the measured solar spectrum.

Visualization web interface

Measurements are recorded by a local computer connected to the measurement equipment is used to record measurements. These are stored in a database that is accessible by a web server. For this reason, it is possible to see and export these measurements from any computer connected to the Internet using only a web browser. Initially the system asks for a user name and an access password. In the home page there is a button to access to a new window with the complete list of photovoltaic modules and one of the defined campaigns of measurements can be selected for each of them. Then, a table is shown with the values of the measurements and the electrical parameters obtained from current-voltage curve, see Figure **4**.



Curva I-V	Espectro	Hora	I_{SC} (A)	V_{OC} (V)	P_{MAX} (W)	IP_{MAX} (A)	VP_{MAX} (V)	FF (%)
		08:06:39	0.186	83.057	8.239	0.137	60.009	53
		08:13:31	0.228	83.417	10.635	0.176	60.505	56
		08:20:31	0.248	83.152	11.561	0.192	60.179	56
		08:48:31	0.396	83.461	18.848	0.303	62.199	57
		09:02:31	0.376	81.231	13.148	0.220	59.691	43
		09:16:31	0.487	82.067	22.634	0.381	59.379	57

Figure 4. T Table with measurements

4. Results and discussions

The visualization web interface allows us to obtain the I–V curve of a measurement (see Figure **5**).

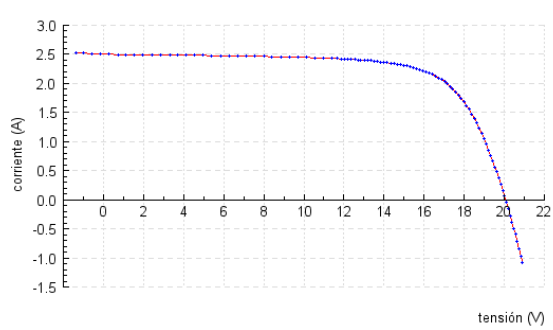


Figure 5. Plot of the I-V of a module

With the developed software it is also possible to predict both the cell temperature of the modules and the spectral distribution of solar irradiance.

The prediction of cell temperature can be obtained from the web interface.

Figure **6**, Figura **7**Figura **8** andFigura **9** show the graphs of the measured hourly temperature and the predicted by each one of the hourly models for the cadmium tellurium (CdTe), amorphous silicon (a-Si), amorphous/microcrystalline silicon (a-Si/ µ-Si) and multicrystalline silicon (mc-Si) modules for Feb. 26, 2102.

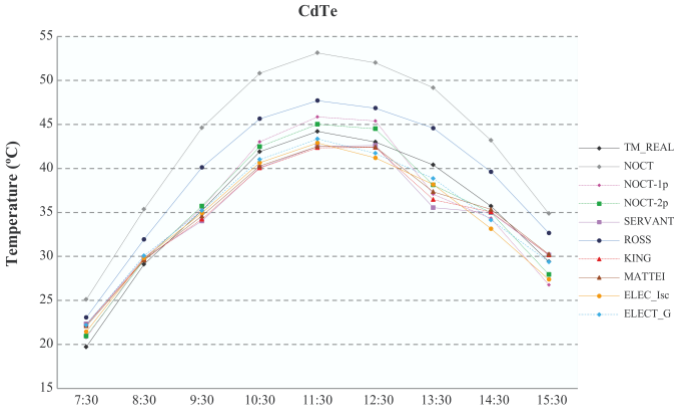


Figure 6. Measured and predicted hourly temperature for CdTe module.

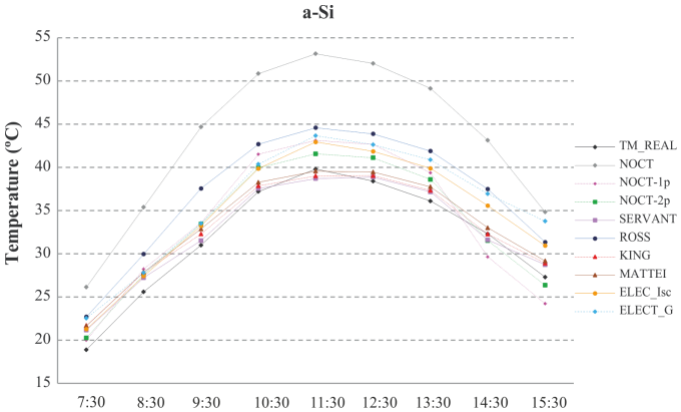


Figura 7. Measured and predicted hourly temperature for a-Si module.

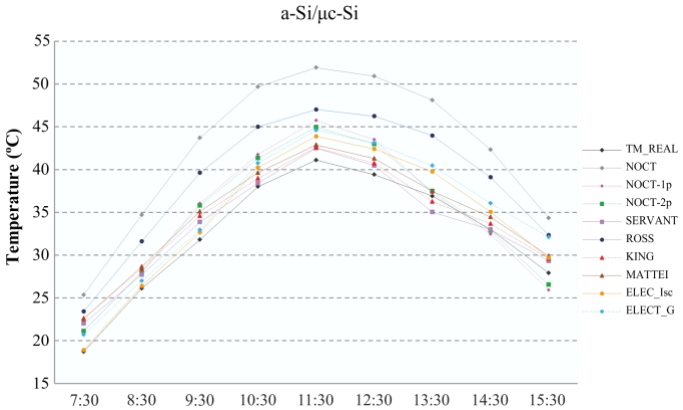


Figura 8. Measured and predicted hourly temperature for a-Si/microcrystalline module.

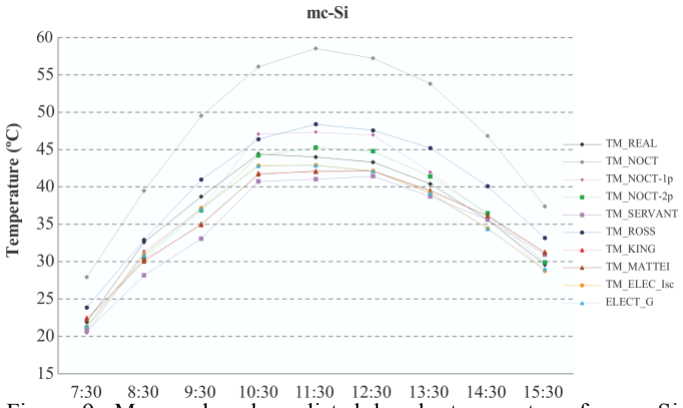


Figura 9. Measured and predicted hourly temperature for mc-Si module.

It is also possible to obtain the spectral distribution of the irradiance at the time of measurement. If the spectral model prediction was active during the measurement, in addition to the measured spectrum, it is possible to visualize the predicted spectrum (see Figure **10**). From each campaign it is possible to access to the table of hourly or daily values.

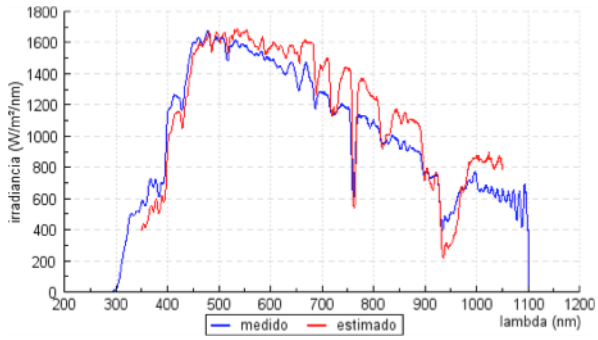


Figure 10. Comparative of a measured spectrum with a predicted one

6. Conclusions

A system that allows the integration of different experimental systems of measurement in a single platform has been developed. This system allows us to obtain at the same time all the necessary information to characterize photovoltaic modules and to study the dependence of their electrical parameters with all the significant meteorological parameters including the spectral distribution of the solar global radiation. Several theoretical prediction models have been implemented for the temperature of the modules and a model that allows us the study of the influence of the variation of the spectrum of the incident radiation on the performance of photovoltaic modules of different technologies has been integrated.

In addition, the system allows us to easily program measurement campaigns, as well as the subsequent evaluation of the registered data.

The implemented methodology allows in a simple way to continue integrating measurement equipment according to the experimental needs of the different research projects that we are carrying out.

This system has proved of great importance in the daily experimental operation of our laboratory.

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