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# Software for the modeling and simulation of PV module's electric characteristics

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**Abstract** - *The aim of this paper is to present a graphical user interface developed under Labview environment that allows, from experimental data, the calculation and extraction of parameters of the one diode model and of the parameters in reverse bias and all other electrical parameters of a PV module. These parameters will be displayed with the different curves, measurement conditions and technological characteristics of the PV module. Based on these extracted parameters, this interface also enables the simulation of the IV characteristic of PV modules. This allows the comparison of experimental results with theoretical results for the purposes of validation and the calculation of STC performances. In addition, a report similar to a datasheet can be printed. The results obtained for several PV modules were very satisfactory. Practical example and results obtained with real system are presented in this paper.*

**Résumé** - *L'objectif de ce papier est de présenter une interface graphique développée sous l'environnement Labview qui permet, à partir de données expérimentales, le calcul et l'extraction des paramètres du modèle à une diode, des paramètres en polarisation inverse, ainsi que tout les autres paramètres électriques d'un module PV. Ces paramètres seront affichés avec les différentes courbes, les conditions de mesures et les caractéristiques technologiques du module PV. Sur la base de ces paramètres extraits, cette interface est aussi capable de simuler les caractéristique I-V des modules PV. Cela permet la comparaison des résultats expérimentaux avec ceux théoriques pour les besoins de validation et du calcul des performances aux STC. De plus un rapport similaire à une fiche technique peut être imprimé. Les résultats obtenus pour plusieurs modules PV on été très satisfaisant. Des exemples pratiques et les résultats obtenus avec un système réel sont présentés dans ce papier.*

**Mots clés**: Modules PV - I-V direct - I-V en polarisation inverse - Extraction de paramètres - Ombrage - Interface graphique Labview.

## 1. INTRODUCTION

The development of photovoltaic solar energy in the world has made the marketing of photovoltaic modules a very promising and profitable market. This has led to the proliferation of players in the field.

The PV module manufacturers provide data characteristics of PV modules under standard test conditions (STC), where the irradiance is 1000 W/m² and the cell temperature ( $T_c$ ) is 25 °C. Some of the parameters typically provided by manufacturers are the maximum power ( $P_{mp}$ ), the short circuit current ( $I_{SC}$ ), the open circuit voltage

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($V_{oc}$), the current and voltage at the maximum power point ($V_{mp}$ and $I_{mp}$, respectively) and temperature coefficients for the short circuit current and open circuit voltage ($\alpha I_{sc}$ and $\beta V_{oc}$, respectively)

The use of this data for the design of PV systems assumes that the values are true and valid on all plant sites. In addition, to predict the behavior of PV modules under all conditions, numerical simulation is used by the implementation of mathematical models describing perfectly their functioning as the one diode model or the modified one to take into account the effect of shadow. These models require knowledge of the values of certain parameters that usually are not provided by the manufacturers. So a complete characterization of PV modules introduced on the market is required.

In this context, we developed a Labview graphical user interface (GUI) that allows obtaining all the settings and data of a PV module from experimental measurements. These experimental measurements are Excel files. For files of the direct I-V characteristic, the interface is currently designed to read those from the PVPM electronic load [1] but a slight modification allows adapting it to files from other data acquisition systems. The developed interface is thus a modeling and simulation tool independent of the data acquisition system.

Labview is graphical software developed by National Instrument. It contains an interactive user interface called "front panel" in which we introduce the data and displays the results. The architecture of the program is contained within another window called diagram. A Labview program is called 'Virtual Instrument (Vi)' [2].

## 2. ARCHITECTURE OF THE PROGRAM AND USED METHODS

To achieve the Graphical User Interface (GUI), several programming techniques have been used. Subroutines were first developed. They allow the execution of certain tasks. Some features available in the library of Labview were also used. The flowchart of figure 1 summarizes the steps of the developed GUI diagram.

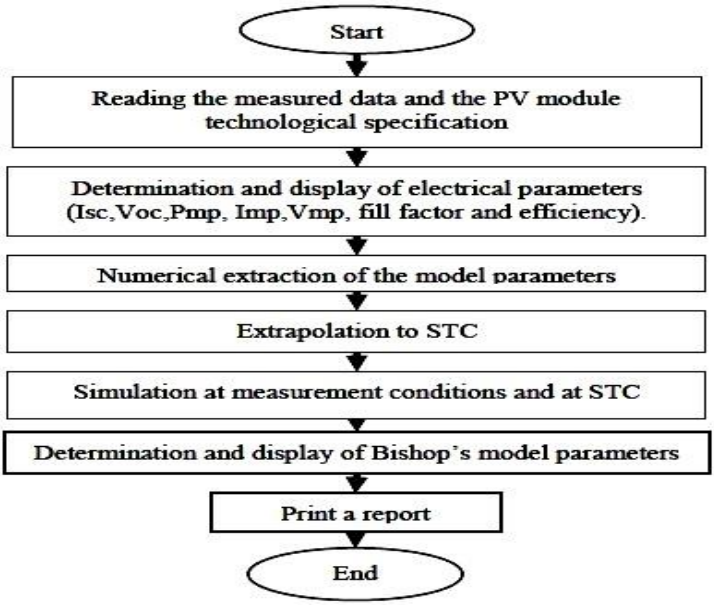



Fig. 1: Steps of the GUI diagram

### 2.1 Reading, processing and analysis of measured data and technological specifications of the PV module

The first step of the main program is reading data measurements of direct and reverse bias $I-V$ characteristic. These data are in Excel spreadsheet files.

The files of the direct $I-V$ characteristic contain values of the current and voltage, the global irradiance and the temperature of the PV module. The files of the reverse bias $I-V$ characteristic contain values of the current and voltage measured in the dark for a solar cell of the same type as those constituting the treated module.

Technological specifications of the PV module (number of cells, active surface and temperature coefficients) are read from a table that can be updated it for a new PV modules. The user does not need to provide this table; the program calls it automatically to read the constants and coefficients of the PV module under study. He has just to select the name of the PV module on the drop-down list in the front panel.

### 2.2 Mathematical modelling and simulation

The model used for this study and implemented in the GUI is the one diode model. It is defined by the equivalent electrical circuit of figure 1 and {Eq. (1)} describing the current-voltage ( $I-V$ ) characteristic [3].

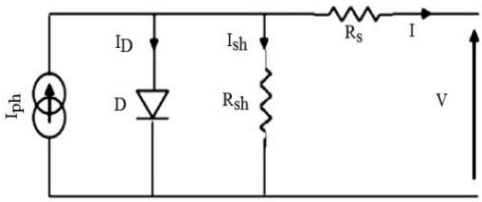



Fig. 2: Equivalent circuit diagram of a PV generator according to the one diode model

$$I = I_{ph} - I_0\left(\exp\left(\frac{V+IR_s}{m.N_s.K.T_c/q}\right)-1\right)-\frac{V+I\,R_s}{R_{sh}} \qquad (1)$$

Where, $I_{ph}$ is the photocurrent, $I_0$ the saturation current of the diode, $m$ the ideality factor, $N_s$ the number of cells in series constituting the PV module, $R_s$ its series resistance, $R_{sh}$ its shunt resistance, $K$ is the Boltzmann constant ($1.38.10^{-23}$ J/K), $T_c$ is the absolute temperature of the cells of the PV module and $q$ the elementary charge.

Parameters $I_{ph}$, $I_0$, $m$, $R_s$ and $R_{sh}$ are not usually provided by the manufacturers of PV modules. To extract them from an $I-V$ characteristic, we used the five-point numerical method [4, 5]. It involves the numerical solution of a system of five nonlinear equations obtained by applying {Eq. (1)} to five specific points of an experimental $I-V$ characteristic [3].

Some authors [6, 7] have presented a PV module simulation tool by implementing the one diode model in Labview. In the interface we developed, the same technique is implemented as step in the form of subroutine (Sub vi) to validate the model and calculate PV module's performances at STC.

To study the effect of partial shading, a term describing the functioning of cells in reverse bias based on Bishop's model [8] is added to the one diode model as described in {Eq. (2)} [9].

$$I = I_{ph} - I_0\left(\exp\left(\frac{V + I R_s}{m.N_s.K.T_c / q}\right) - 1\right) - \frac{V + I R_s}{R_{sh}} \times \left(1 + a\left(1 - \frac{V + I R_s}{V_{br}}\right)^{-n}\right) \quad (2)$$

Where $V_{br}$ is the break down voltage, $a$ and $n$ fitting parameters.

The parameters of this term are extracted by fitting an $I-V$ curve of a solar cell in the dark and in reverse bias. This cell must be of the same type as those composing the PV module under test [10]. The method used for the fitting is the ''Levenberg Marquardt'' algorithm which is implemented in Labview.

### 2.3 Translation equations

Since the parameters are extracted from experimental measurements under natural reference conditions of illumination and cell temperature ($G_{ref}$ and $T_{c,ref}$), equations of translation are necessary for values under other conditions such as STC.

For this, Mermoud equations [11] are used for the photocurrent ($I_{ph}$) and the saturation current ($I_0$), De Soto *et al*. [12] for the shunt resistance ($R_{sh}$) and IEC 60891 Standard [13] for the short circuit current ($I_{sc}$) and open circuit voltage ($V_{oc}$). So the implemented equations are:

$$I_{ph} = \frac{G}{G_{ref}} \times \frac{M}{M_{ref}} \times \left(I_{ph_{ref}} + \alpha_{I_{sc}}(T_c - T_{c_{ref}})\right) \quad (3)$$

$$I_0 = I_{0_{ref}}\left(\frac{T_c}{T_{c_{ref}}}\right)^3 \times \exp\left(\frac{q_{E_g}}{m\,K}\left(\frac{1}{T_{c_{ref}}} - \frac{1}{T_c}\right)\right) \quad (4)$$

$$\frac{R_{sh}}{R_{sh_{ref}}} = \frac{G_{ref}}{G} \quad (5)$$

$$I_{sc} = I_{sc_{ref}} \times \frac{G}{G_{ref}} + \alpha_{I_{sc}}(T_c - T_{c_{ref}}) \quad (6)$$

$$V_{oc} = V_{oc_{ref}} + m\frac{K T_{c_{ref}}}{q}\ln\left(\frac{G}{G_{ref}}\right) + \beta_{V_{oc}}(T_C - T_{c_{ref}}) \quad (7)$$

Where, $G_{ref}$, $T_{c,ref}$, $I_{ph_{ref}}$, $I_{sc_{ref}}$, $V_{oc_{ref}}$, $I_{0_{ref}}$ and $R_{sh_{ref}}$ are respectively, the solar irradiance, the cell temperature, the photocurrent, the short circuit current, the open circuit voltage, the saturation current and the shunt resistance at reference conditions. $E_g$ is the gap, $\alpha I_{sc}$ and $\beta V_{oc}$ are respectively temperature coefficients of short circuit current and open circuit voltage. $M / M_{ref}$ is the spectral correction. It is given by an empirical equation based on the number of air mass.

There are still two parameters to be translated, series resistance $R_{sh}$ and the ideality factor m. The serial resistance affects the slope of the $I-V$ characteristic in the region where the module operates as a voltage generator, but this variation with the temperature is not significant to induce a significant error on the maximum power point, it is therefore admitted that it remains constant [12]. We also consider that the ideality factor m is not affected by the temperature.

## 3. LABVIEW GRAPHICAL USER INTERFACE (GUI) DEVELOPED

The developed GUI is very interactive. The results are displayed in three different pages accessible by clicking. The first page is for the treatment and results at measurement conditions (figure 3), the second page (figure 4) for the simulation, validation and STC results and the third page (figure 5) is devoted to the characterization of the solar cells in reverse bias.

From this GUI, we can also order the printing of a text report similar to a datasheet that contains all information appearing in the front panel.

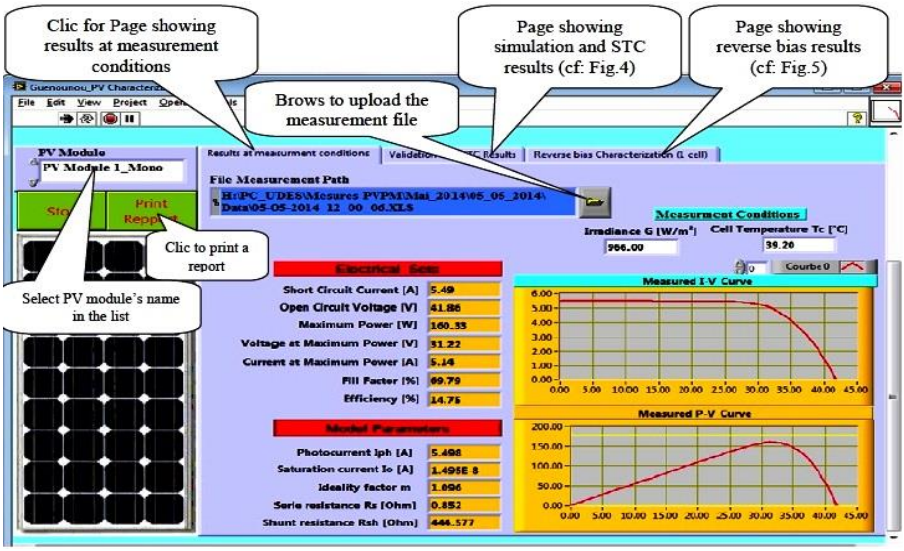



Fig. 3: A view of the developed GUI when the page showing results at measurement conditions is activated

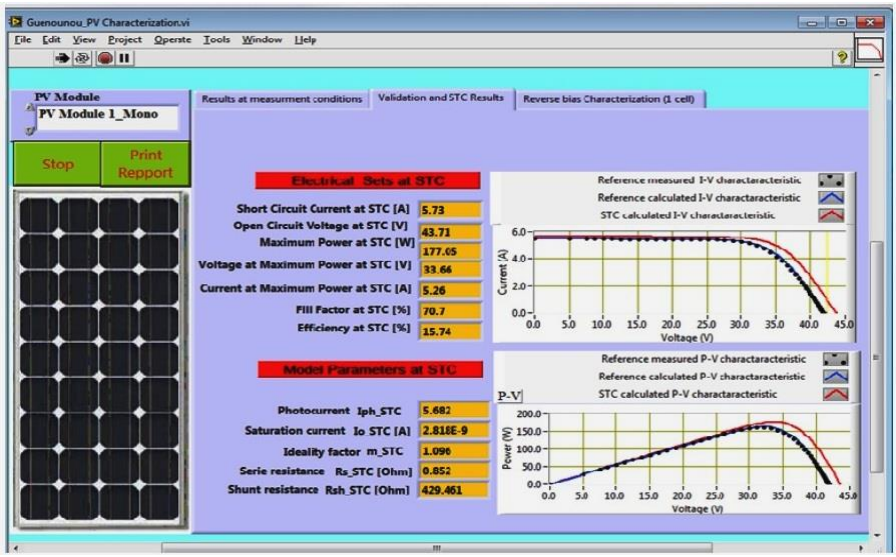



Fig. 4: A View of the GUI when the page showing simulation and STC results is activated

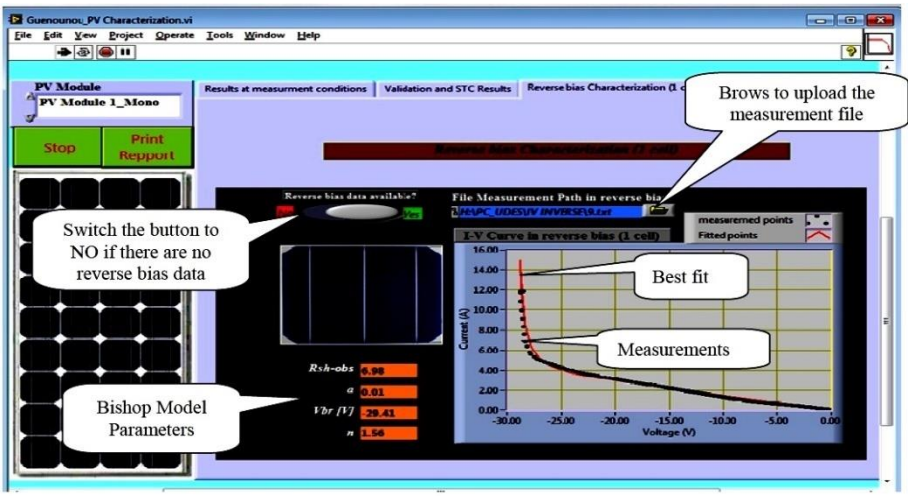



Fig. 5: A view of the GUI when the page showing results of reverse bias characterisation is activated

## 4. VALIDATION AND RESULTS

### 4.1 Direct IV characteristics

The results of the interface developed were validated on two types of files obtained for different PV modules with two different acquisition systems used at the level of the Unit of Development of the Solar Equipment, UDES [1, 14, 15].

In this paper, we present the results obtained for three PV modules of different technologies (single-crystalline silicon, polycrystalline silicon and amorphous silicon). The data of the files comprise the current and voltage measurements of the $I-V$ characteristic as well as the measurement conditions, which are temperature and solar irradiance.

Figure 6 to 8 show the direct current-voltage ($I-V$) and power-voltage ($P-V$) measured characteristics (points), simulated at the measurement conditions (blue curves) and simulated at STC (red curves).

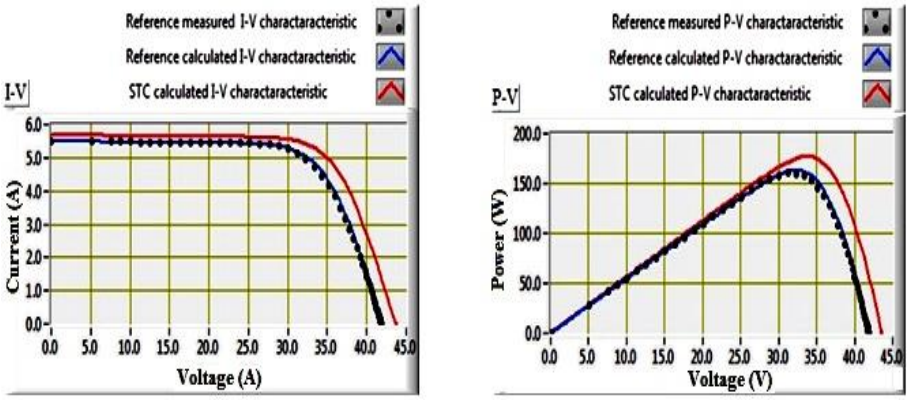



Fig. 6: $I-V$ and $P-V$ characteristics measured (dots), simulated at measurement conditions (continued blue line) and simulated at STC (continued red line) for the monocristalline silicon PV module

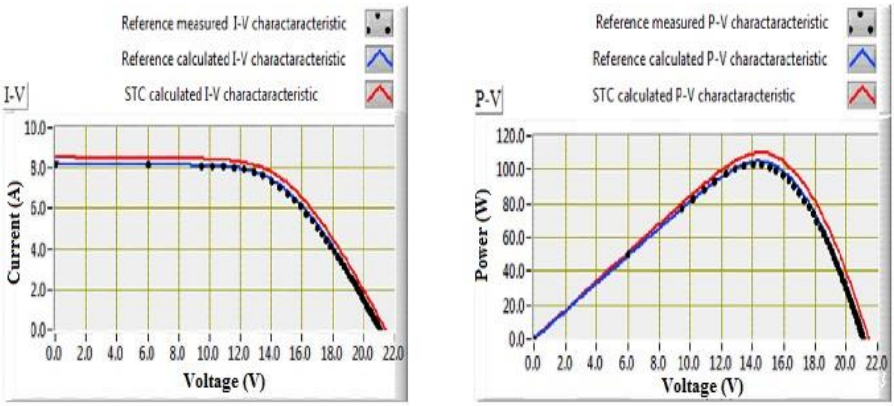



Fig. 7: $I-V$ and $P-V$ characteristics measured (discontinued points), simulated at measurement conditions (continued blue line) and simulated at STC (continued red line) for the polycristalline silicon PV module

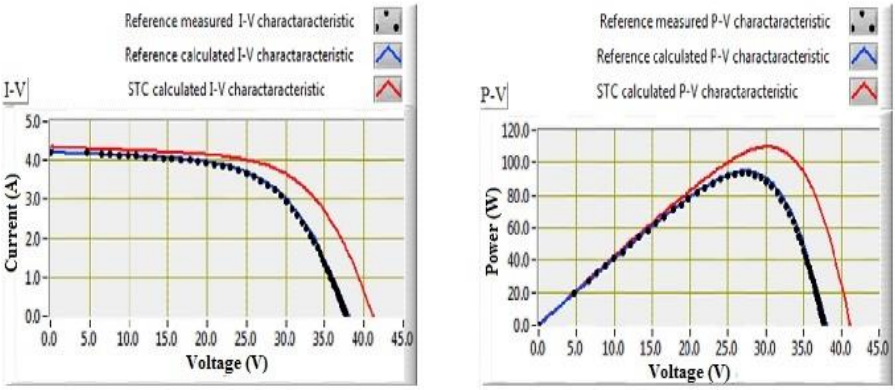



Fig. 8: $I-V$ and $P-V$ characteristics measured (discontiued points), simulated at measurement conditions (continued blue line) and simulated at STC (continued red line) for the amorphous Silicon PV module

Beyond the inevitable measurement errors, we note that each group of model parameters extracted reproduces perfectly the corresponding $I-V$ characteristic.

To validate the results obtained at the STC, we compared some performances provided in the datasheets of the PV modules with those calculated using the developed tool (**Table 1**). The electrical parameters considered for comparison are: the short circuit current ($I_{sc}$), the open circuit voltage ($V_{oc}$), the maximum power ($P_{max}$), the fill factor ($FF$) and the efficiency ($\eta$).

We note that the gaps are very low for the single-crystalline silicon PV module and are within the margin of tolerance specified by the manufacturer (± 5% for $P_{max}$). For amorphous the silicon PV module, except for a small decrease of the fill factor (about 5 %), all other values have increased compared to the values of the datasheet, especially for the short circuit current witch the gap is almost 13 %.

But this is normal and other authors also found considerable gaps with this type of PV modules [16]. For polycrystalline silicon module, except for the short circuit current

and open circuit voltage where the gaps are acceptable, there is a significant drop in the max power, the fill factor and the efficiency. Observing several measurements, we believe that this is due to the significant increase in the series resistance that affects the fill factor, the max power and therefore the efficiency.

**Table 1:** Comparison between the performance provided in the data sheets of PV modules and those calculated at STC

| PV Module | Parameter | Datasheet value | Calculated value at STC | Gap = (calculated – datasheet) . 100 / datasheet |
|---|---|---|---|---|
| PV Module 1 (Si-mono) | Isc (A) | 5.76 | 5.73 | -0.52 % |
| | Voc (V) | 43.2 | 43.71 | 1.18 % |
| | Pmax (W) | 185 | 177.05 | -4.30 % |
| | FF (%) | 72 | 70.7 | -1.81 % |
| | η (%) | 14.4 | 15.74 | 9.31 % |
| PV Module 2 (Si-poly) | Isc (A) | 8.20 | 8.54 | 4.15 % |
| | Voc (V) | 22.3 | 21.41 | -3.99 % |
| | Pmax (W) | 135 | 109.85 | -18.63% |
| | FF (%) | 73.8 | 60.04 | -18.6 4% |
| | η (%) | 15.6 | 12.54 | -19.62 % |
| PV Module 3 (a-SI) | Isc (A) | 3.89 | 4.39 | 12.85 % |
| | Voc (V) | 40.0 | 41.08 | 2.70 % |
| | Pmax (W) | 100 | 109.61 | 9.61 % |
| | FF (%) | 64.2 | 60.81 | -5.28 % |
| | η (%) | 6.9 | 7.61 | 10.29 % |

### 4.2 Reverse biased solar cell and effect of partial shadow

The method of characterization used in reverse bias relates to the extraction of parameters of an individual solar cell in the dark. Figure 5 from above shows the results obtained on a single-crystalline silicon solar cell of 125 cm × 125 cm. The utility of Bishop's parameters has been studied in a recent paper [10].

Figure 9 shows the results of validation of the model of {Eq. (2)} for a single crystalline silicon PV module provided with two bypass diodes. These are the measured and simulated $I-V$ characteristics when one of solar cells of the PV module is shaded with different rates.

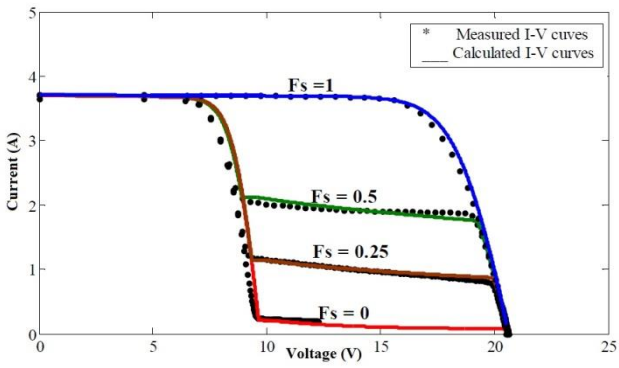



Fig. 9: Measured and simulated $I-V$ characteristics of a monocristalline PV module for different transmittances of shade in one of its solar cells

### 4.3 Printed report

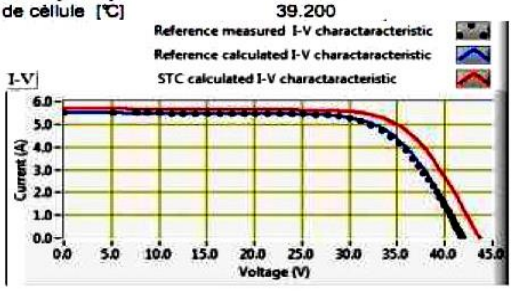
An example of a report printed from the developed GUI is shown in figure 10.

Rapport de traitement Outdoor 03/07/2014

**Module JT-185-M**
**S= 1.125m², Ns=72**

Conditions et courbe de référence (Mesure):

Eclairement solaire [W/m²] 966.000
Température de cellule [°C] 39.200




Paramètres éléctriques du module PV:

| | Valeurs mesurées | Valeurs aux STC |
|---|---|---|
| Courant Isc [A] | 5.487 | 5.729 |
| Tension Voc [V] | 41.865 | 43.711 |
| Puissance max [W] | 160.331 | 177.055 |
| Courant Imp [A] | 5.135 | 5.260 |
| Tension Vmp [V] | 31.222 | 33.658 |
| Rendement [%] | 69.793 | 70.701 |
| Facteur de forme [%] | 14.753 | 15.738 |

Paramètres du modèle à une diode:

| | Valeurs de référence: | Valeurs aux STC: |
|---|---|---|
| Photocourant [A] | 5.498E+0 | 5.682E+0 |
| Courant saturation [A] | 1.495E-8 | 2.818E-9 |
| Résistance série [Ohm] | 8.516E-1 | 8.516E-1 |
| Facteur d'idéalité | 1.096E+0 | 1.096E+0 |
| Résistance shunt [Ohm] | 4.446E+2 | 4.295E+2 |

Paramètres du modèle inverse de Bishop:

| Rsh_obs | a | Vbr | n |
|---|---|---|---|
| 6.985E+0 | 6.754E-3 | -2.941E+1 | 1.559E+0 |

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Fig. 10: Report generated by the GUI

## 5. CONCLUSION

The original developed Graphical Unit Interface (GUI) is highly valuable because of the importance of parameters that it enables to compute. In addition, its use is convenient and open to all PV engineering specialists without knowledge of Labview. It is a reliable interactive tool for modelling, simulation and testing of PV modules.

Although it requires experimental input data files, it is not connected to a data acquisition system. In fact, it can be used for both natural and laboratory studies. It can be used as a second part of a virtual laboratory whose first part is developed to generate the IV measurements.

In this paper, we presented the results of validation, in direct polarization, of three PV modules (c-Si, poly-Si and a-Si) which proved to be very positive. But several other types of PV modules can be studied with this GUI

Moreover, we validated the results in reverse bias and showed the usefulness and the importance of the parameters in reverse bias with a concrete example.

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