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Abstract

A comparison between the experimental current-voltage (I-V) and power-voltage (P-V) characteristics of PhotoVoltaic (PV) modules, and the prediction of an explicit empirical model has been carried out. The model consists of an explicit expression for the current as a function of the voltage; the only inputs are the parameters that are always directly available in the manufacturer's datasheet. The comparison was carried out on four representative PV technologies, based on polycrystalline Si, Heterojunction with Intrinsic Thin layer (HIT), Copper Indium Gallium Selenide (CIGS), and Cadmium Telluride (CdTe). Conditions of high and low solar irradiance were investigated and the comparison reveals that the model replicates the experimental I-V and P-V curves to a very good degree of accuracy for all the considered working conditions and PV technologies. This validation sets a turning point in PV modelling, as it enables a reliable use of this accessible model.

Keywords: CdTe, CIGS, HIT, I-V and P-V characteristics.

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1. Introduction

Nowadays, the main commercial Photovoltaic (PV) technology is based on crystalline silicon. These solar devices represent the first generation of photovoltaics and cover the 90% of the market. The remainder of the market is covered by thin film technologies mainly based on CdTe, CIGS, and amorphous silicon. These products, owning to the second generation of photovoltaics and characterized by a slightly lower efficiency than the devices from the first one, are today entering the market especially because of their lower manufacturing cost and continuous increase in performances [1]. In the future, a third generation of photovoltaics should commercially guarantee higher efficiencies and lower costs. Dye Sensitized Solar Cells (DSSC), Organic PV (OPV), Intermediate electronic Band (IB) and Multiple Exciton Generation (MEG) are only some examples of third generation devices that today are either not commercially available or have a very small market [2]. Even if first and second generation technologies are based on different physical mechanisms and come from a wide range of fabrication techniques, their electrical output in terms of current and power-voltage characteristics are only slightly different.

Effective use of PV modules requires reliable modelling methods, aiming at predicting the behaviour of a PV system at conditions different from those characterized by the manufacturer's datasheet. Such methods are helpful for monitoring the performance [3, 4, 5, 6] and the losses in solar systems [7-10], for forecasting the produced power [11-15], and for development and testing of maximum power point tracking algorithms [16-18]. Reliable models are also needed for system fault diagnosis [19, 20] and to study and evaluate the behaviour of defective PV cells. Description of known defects in PV cells is reported in [21-23], while in-depth investigations of the thermal effects of defects are proposed in [24-26] where a finite element approach to model some classes of defects commonly found in PV cells is presented.

Equivalent circuits, including a photocurrent source, one or more resistors, and one or more nonlinear elements typically represented by semiconductor diodes, are the most common topology for modelling crystalline Si PV devices [27]. A widely used equivalent circuit is the "single-diode" model – often referred to as the "five-parameter" model (Fig. 1), as it may be completely characterized by five parameters: shunt and series resistances, diode ideality factor, photocurrent, and diode reverse saturation current. The single diode model ensures high accuracy through three characteristic points in the PV datasheet (open-circuit voltage, short-circuit current, and maximum power point), it guarantees that the maximum point generated by the mathematical model coincides with the datasheet, and provides an excellent fit between to the experimental current-voltage (I-V) curve [28].

The five-parameters model is accurate enough for modelling and simulation of crystalline Si PV modules, but the applicability to other PV technologies (especially owning to the second generation of photovoltaics) is found to be limited since the single-diode equivalent circuit fails to describe the significantly different physical processes of converting radiant energy into electrical energy [1]. For this reason, today many researchers are focusing in the development of new models capable of describing the behaviour of different technologies, such as for example thin-films [29].

The explicit empirical model for general PV devices - that was introduced in order to enable modelling based only on the parameters that are always listed in the datasheet of solar devices - overcomes these drawbacks. It was initially introduced in [30] and then applied in [31, 32] in a revised form for assessing the mismatch effect due to the use of different classes of PV modules in large-scale solar parks. A revised form of the model was validated experimentally for operation at Maximum Power Point (MPP) [33], showing a very good prediction performance, better than the ones obtained with the golden standard in PV modelling, i.e. the five-parameters model. The explicit empirical model has been lately improved, introducing a correction factor that leads to a good match with the experimental electrical characteristics also for operating points other than the MPP [34].

As mentioned, the model is based exclusively on the parameters commonly found in the datasheets provided by the manufacturers, and explicit – and therefore quite easy to implement in computer-aided calculations. Explicit models are today increasingly being studied [35] due to these characteristics, and they represent a useful tool not only for scientists, but also in all practical cases for PV plant designers, Operation and Maintenance (O&M) personnel, and in general for PV professionals. In particular, the model has a distinct advantage in terms of computational complexity and time, both because its explicit form, and because the input parameters are readily available and do not need to be computed in advance (see for example [36-44]).

Validation of this model along the entire I-V and P-V characteristics and for different working conditions is therefore of paramount importance for ensuring that this very accessible tool does have the necessary accuracy and reliability for professional and scientific purposes. In this work, we focus on the validation of the model for the entire current-voltage (I-V) and power-voltage (P-V) characteristics of four representative commercial PV modules based on polycrystalline silicon, HIT technology, CIGS, and

CdTe. The validation was carried in the range [900 – 1,000W/m^2], and in the range [300 - 500W/m^2] in order to consider both high and low level of solar irradiance.

The paper is organized as follows: the next Section is on the description of the model under validation. Section 3 presents the test facility. Section 4 deals with results and discussion. Section 5 presents the conclusions.

2. The explicit empirical model

The behaviour of a solar cell is commonly modelled with the well-known five-parameter equivalent model represented in Figure 1.

The solar cells is modelled by an ideal current source in parallel with a diode. The circuit is described by the following equation:

$$I = I_{Ph} - I_o \times \left[e^{(V+IR_s)/nV_t} - 1 \right] - \frac{V + IR_s}{R_{sh}} \tag{1}$$

where I_{Ph} (A) is the light generated current (i.e. the short circuit current neglecting the parasitic resistances), I_o (A) is the dark saturation current due to recombination, n is the ideality factor, V_t (V) is the thermal voltage, R_s (Ω) is a series resistance, and R_{sh} (Ω) is a shunt resistance. The light generated current is directly proportional to the solar irradiance [45]:

$$I_{Ph} = \frac{G}{1000} \times \left[I_{Lref} + \alpha \cdot (T_c - 25) \right] \tag{2}$$

where G (W/m^2) is the solar irradiance, 1000W/m^2 is the solar irradiance at Standard Test Conditions (STC), I_{Lref} (A) is the short circuit current at STC, α (A/°C) is the current-temperature coefficient at STC, T_c (°C) is the cell temperature and 25°C is the STC cell temperature.

Combining equations (1) and (2), we can write:

$$I = \frac{G}{1000} \times \left[I_{Lref} + \alpha \cdot (T_c - 25) \right] - I_o \times \left[e^{(V+IR_s)/nV_t} - 1 \right] - \frac{V + IR_s}{R_{sh}} \tag{3}$$

The dark saturation current I_o is a function of the cell temperature and can be written as [46]:

$$I_o = I_{oref} \cdot e^{\left(\frac{E_{go}}{V_{to}} - \frac{E_g}{V_t}\right)} \cdot \left(\frac{T_c}{25}\right)^3 \quad (4)$$

where I_{oref} (A) and V_{to} (V) are the saturation current and the thermal voltage at STC, respectively, E_g (V) is the energy bandgap, while E_{go} (V) is the energy bandgap at T=0 K. Combining equations (3) and (4), we can write:

$$I = \frac{G}{1000} \times \left[I_{Lref} + \alpha \cdot (T_c - 25) \right] + I_{oref} \cdot e^{\left(\frac{E_{go}}{V_{to}} - \frac{E_g}{V_t}\right)} \cdot \left(\frac{T_c}{25}\right)^3 - I_{oref} \cdot \left(\frac{T_c}{25}\right)^3 \cdot e^{\left(\frac{E_{go}}{V_{to}} - \frac{E_g}{V_t} + \frac{(V+IR_s)}{n \cdot V_t}\right)} - \frac{V + IR_s}{R_{sh}} \quad (5)$$

The series resistance R_s is also a function of the operating conditions being [47]:

$$R_s = \frac{V_{OC}}{I_{SC}} \times r_s \quad (6)$$

where V_{oc} (V) and I_{sc} (A) are the open circuit voltage and the short circuit current at arbitrary conditions of solar irradiance and cell temperature respectively, and r_s is the normalized solar cell’s resistance.

The open circuit voltage V_{oc} depends on the cell temperature and can be written as [48]:

$$V_{OC} = V_{OC,STC} + \beta \cdot (T_c - 25) \quad (7)$$

where $V_{OC,STC}$ (V) is the open circuit voltage at STC and β (V/°C) is the voltage-temperature coefficient at STC.

Finally, the short circuit current I_{sc} depends on the solar irradiance and can be written as [43]:

$$I_{SC} = \frac{G}{1000} \times I_{SC,STC} \quad (8)$$

where $I_{SC,STC}$ (A) is the short circuit current at STC.

Substituting (7) and (8) in (6), then (6) in the third and fourth term of (5), we obtain:

$$I = \frac{G}{1000} \times \left[I_{Lref} + \alpha \cdot (T_c - 25) \right] + f_1(V) + f_2(I, G, T_c) + \exp(V, I, G, T_c) \quad (9)$$

where f_1 is a linear function of the voltage, f_2 is a function of the current and the operating conditions (thus similar to the first term of eq. (5)), and the exponential depends on both the electrical variables and on the operating conditions. These three functions can be grouped in an empiric expression able to provide a correct current value for each voltage value in the range [0-V_{OC}], whatever the environmental condition is:

$$f_1(V) + f_2(I,G,T_c) + \exp(V,I,G,T_c) = -\frac{G}{1000} \cdot \frac{e^{m \cdot [V - \beta \cdot (25 - T_c)]} - 1}{e^m - 1} \tag{10}$$

where m is an empiric exponential factor.

Combining (9) and (10), a more suitable empirical expression where the current and the voltage are in a per unit representation [34] is:

$$I_{pu} = \frac{G}{1000} \left[I_{L,ref} + \alpha \cdot (T_c - 25) - \frac{e^{m \cdot [V_{pu} - \beta \cdot (25 - T_c)]} - 1}{e^m - 1} \right] \tag{11}$$

where I_{pu} (p.u.) is the per unit current referred to $I_{SC,STC}$, $I_{L,ref}$ (p.u.) is the per unit irradiance referred to 1000W/m^2, V_{pu} (p.u.) is the per unit voltage referred to $V_{OC,STC}$, α' (1/°C) is the current-temperature coefficient referred to $I_{SC,STC}$ (α' = α/$I_{SC,STC}$) and β' (1/°C) is the voltage-temperature coefficient referred to $V_{OC,STC}$ (β' = β/$V_{OC,STC}$).

The model represented by equation (11) has a wide applicability and presents the following pros:

- it can be used considering only the electrical parameters which can always be found in the solar cell/PV module datasheet. This represents a clear advantage as the commonly used models require parameters that cannot be found in the manufacturer's datasheets, such as the light-generated or PV current, the series and shunt resistances, the diode ideality constant, the diode reverse saturation current, and the bandgap energy of the semiconductor [49];
- it is explicit, which is a very desirable feature for simulation applications, especially when the model is to be used repeatedly (as, for example, in the case of PV emulators [50]). Simulation times can be significantly reduced by avoiding the numerical iterations required by implicit equation models [51];
- it can be used for any type of PV technology owning to first and second generation photovoltaics as, for example, crystalline Si, CdTe, CIGS, etc.;

- it can be used for any type of PV device: solar cells, PV modules, PV strings and fields. The extension to the model to these latter has been shown in [31] and comes from the Kirchhoff's laws and the induction principle;
- it can be used to calculate any working conditions of the I-V and P-V characteristics (generic, at MPP, and in open and short circuit configurations).

3. Validation of the explicit empiric model

The empirical model has been tested starting from the I-V and P-V characteristics of four PV modules mounted in our Laboratory [52]. The four PV modules are representative of different technologies: polycrystalline Si, CdTe, CIGS, and HIT. The solar cells of this latter are made of a thin mono crystalline silicon wafer surrounded by ultra-thin amorphous silicon layers. The different parameters of the considered PV devices are reported in Table 1.

The following instruments have been used to measure and log the different working conditions:

- an ISO9060 first class thermopile global radiometer type C100RDPA153 from LSI Lastem S.r.l. measuring the global solar irradiance (with a daily uncertainty less than 5%);
- a contact probe type DLE124 produced by LSI Lastem S.r.l. (with an accuracy of ±0.15°C);
- two data loggers type E-Log produced by LSI Lastem S.r.l.;
- a shunt type SHP300A60-Compact produced by Hobut Ltd. calibrated with an accuracy better than 0.01%.

Figure 2 shows two of the considered PV modules, while in Figure 3 the data logger and the shunt are visible.

The I-V curves have been plotted using a variable resistive load. Voltages and currents have been measured using the test facility described in [52]. The voltages are measured with an accuracy better than 0.01%, while the currents have an accuracy better than 0.1%.

4. Results

This section presents the comparison between the I-V and P-V characteristics evaluated by the empirical model and those obtained from the experimental measurements. Two different environmental conditions corresponding to high (in the range [900 - 1,000W/m^2]) and low (in the range [300 - 500W/m^2]) solar irradiance have been considered.
The analysis closes this section.

4.1. High solar irradiance

Figures from 4 to 7 depict the I-V and P-V characteristics for a high level of solar irradiance for Q.Pro, HIP 215 NHE5, UF-95, and FS-272 respectively.

The analysis of the eight plots leads to the following conclusions:

- Q.Pro module (poly-Si). The correspondence between the measured and the estimated curves is fully satisfactory. The model accurately predicts both the open circuit voltage and the short circuit current. The power and the voltage at MPP are slightly overestimated;
- Sanyo HIP module (HIT technology). Again, the curves calculated using the explicit empirical model adequately fit the experimental characteristics. In this case, the open circuit voltage is slightly underestimated, while the predicted short circuit current almost corresponds with the measured one. The power and the voltage at MPP are accurately predicted;
- UF95 module (CIGS). The predicted and the experimental curves correspond very well. As in the case of the previous considered technology, only the open circuit voltage is slightly underestimated, while the short circuit current is well estimated. The power and the voltage at MPP are very well predicted;
- FS-272 module (CdTe). Also for this technology, the correspondence between the model and the measurement is very good, and the open circuit voltage is slightly underestimated. The power and the voltage at MPP are accurately predicted.

From a general and quantitative point of view, the results are given in terms of statistical errors. The coefficient of determination R^2 and the root mean square deviation RMSD are listed in Table 2. The obtained correlation factors, consistently larger than 0.98 and mostly equal to 0.99, show the high performance of the explicit empirical model for any technology.

4.2. Low solar irradiance

Figures from 8 to 11 depict the I-V and P-V characteristics for a low level of solar irradiance for Q.Pro, HIP 215 NHE5, UF-95, and FS-272 respectively.

The analysis of the eight plots leads to the following conclusions:

- Q.Pro module (poly-Si). The correspondence between the measured and the estimated curves is fully satisfactory. The model accurately predicts both the open circuit voltage and the short circuit current. The power at MPP is slightly underestimated;
- Sanyo HIP module (HIT technology). Also for this technology, the curves calculated by the model adequately fit the experimental characteristics. The short circuit current and the open circuit voltage are very well predicted. The power at MPP is barely underestimated;
- UF95 module (CIGS). The model qualitatively performs as in the case of the previous considered technology and the results are accurate;
- FS-272 module (CdTe). The correspondence between the model and the measurement is very good. Only for this technology, the power at MPP is overestimated.

With reference to the statistical errors, the coefficient of determination R^2 and the RMSD are listed in Table 3. The obtained correlation factors, that for currents and voltages are consistently larger than 0.97, show the high performance of the proposed model for any technology.

Moreover, we have compared the accuracy of the proposed model with the accuracy of the R_p-model and of the two-diode models of [43], considering the error values reported in the last two columns of the tables 5-7 (Poly-Si and thin film, respectively) and of the Figures 12-13 of [43], valid for STC. Table 4 compares the errors of the proposed model with of the other two models reported in [43]. As it can be observed, the proposed model has a limited error, comparable with that of well-established models, the largest difference being observed for the V_{OC} of thin film modules. For the other main points of the I-V characteristic, the proposed model returns almost always more accurate values.

Summarizing, the proposed model performs well at both high and low solar radiation conditions. In some cases, a mismatch of the MPP or the Voc is observed. We speculate that this limitation is due to the single-diode equation, used to derive the proposed model. A more accurate starting model, such as the double-diode model is expected to perform better, but it would require two empirical indexes, m_1 and m_2, to follow the characteristic curves of the two diodes, thus complicating the proposed model, which now is effective and fast because it does not require any iterative approach as it happens for other models. Moreover, other two reasons of the mismatch are the spectral effects (in particular for the CdTe modules) [53]-[54] and the angle of incidence, in particular for the low irradiance measurements.

Finally, this validation represents a key result in the modelling of PV devices, as the model shows a wide applicability, presenting the following pros:

- it can be used considering only the electrical parameters which can always be found in the solar cell/PV module datasheet. This represents a clear advantage as the commonly used models require parameters that cannot be found in the manufacturer's datasheets, such as the light-generated or PV current, the series and shunt resistances, the diode ideality constant, the diode reverse saturation current, and the bandgap energy of the semiconductor;
- it is explicit, which is a very desirable feature for simulation applications, especially when the model is to be used repeatedly (as, for example, in the case of PV emulators [50]). Simulation times can be significantly reduced by avoiding the numerical iterations required by implicit equation models [51];
- it can be used for any type of PV technology belonging to first and second generation photovoltaics as, for example, crystalline Si, CdTe, CIGS, etc.;
- it can be used for any type of PV device: solar cells, PV modules, PV strings and fields. The extension to this new model to these latter has been shown in [31] and comes from the Kirchhoff's laws and the induction principle;
- it can be used to calculate any working conditions of the I-V and P-V characteristics (generic, at MPP, and in open and short circuit configurations).

5. Conclusions

This paper presents the experimental validation of the explicit empirical model for general PV devices.

The model was tested at different operating conditions corresponding to low and high values of solar irradiance. Moreover, the tests were performed on four different representative PV technologies, i.e. polycrystalline Si, HIT, CIGS, and CdTe - belonging to the first and the second generation of photovoltaic technologies, respectively.

The model, that had already been tested at maximum power point [33], has shown to be able to predict the key features of the actual I-V and P-V characteristics to a very good degree of approximation. The curves measured experimentally almost always lay on the predicted ones and the obtained results in terms of statistical errors quantitatively confirm the excellent performance of the model.

Thus, the model represents a very useful and accessible tool not only for scientists but also in all practical cases for PV professionals, such as PV plant designers and Operation and Maintenance (O&M) personnel. Moreover, its ability to perform well both at high and at low values of solar irradiance overcomes one of the most common problems occurring when using the methods coming from the ideal PV circuit model that suffers of accuracy when solar irradiance is low [55].

The model slightly underestimates the open circuit voltage for high values of irradiance. Therefore, a future work will be focused on the improvement of the proposed model to fit best also to this operating condition. In order to do this, the analogy with the seven-parameters models that considers a second diode – with an ideality factor of "2" - parallel connected to the one indicated in Fig. 1 will be considered for obtaining a new empirical model. In this, the contribution given by a second exponential term will take into account the behaviour of the different materials constituting the PV modules used for the test of the model.

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Table 1 Electrical characteristics at STC (except for NOCT)

Photovoltaic module	**Q.Pro**	**HIP 215NHE5**	**UF-95**	**FS-272**
Material Technology	Poly-Si	HIT	CIGS	CdTe
Nominal power P_n (W)	230	215	95	72.5
Tolerance on the nominal power (W)	+5.0/-0	+10/-5%	+5.0/-0	±3.6
Short circuit current I_{SC} (A)	8.30	5.61	1.68	1.23
Open circuit voltage V_{OC} (V)	36.6	51.6	78.0	88.7
Current at maximum power point I_{mp} (A)	7.84	5.13	1.53	1.09
Voltage at maximum power point V_{mp} (V)	29.6	42.0	62.1	66.6
Current/temperature coefficient α (%/K)	+0.04	+0.03	0.00	+0.04
Voltage/temperature coefficient β (%/K)	-0.41	-0.03	-0.38	-0.25
NOCT (°C)	47	48	51	45

Table 2 Statistical Errors – High Solar Irradiance

	Power		**Current**		**Voltage**	
PV module	**RMSD [W]**	**R^2 [ ]**	**RMSD [A]**	**R^2 [ ]**	**RMSD [V]**	**R^2 [ ]**
Q.PRO	1.59	0.98	0.37	0.98	1.58	0.98
HIP215NHE5	4.05	0.99	0.03	0.99	0.45	0.99
UF-95	1.30	0.99	0.19	0.99	0.56	0.99
FS-272	2.51	0.98	0.03	0.99	0.27	0.99

Table 3 Statistical Errors – Low Solar Irradiance

	Power		**Current**		**Voltage**	
PV module	**RMSD [W]**	**R^2 [ ]**	**RMSD [A]**	**R^2 [ ]**	**RMSD [V]**	**R^2 [ ]**
Q.PRO	1.05	0.99	0.05	0.99	1.01	0.99
HIP215NHE5	5.40	0.94	0.10	0.97	2.25	0.97
UF-95	1.90	0.97	0.03	0.98	1.21	0.99
FS-272	0.93	0.99	0.01	0.99	1.25	0.99

Table 4 Per cent error values for the main points of the I-V curve and of the P-V curve between the proposed model and both the R_p-model and the two-diode model of [43].

Technology	PV module	$e_{P_{MPP}}$	$e_{V_{MPP}}$	$e_{V_{OC}}$
Poly-Si	**Q.PRO**	0.09	3.00	-0.001
	S36/KC200GT (R_p-model) [42]	0.219	2.055	0.2
	S36/KC200GT (two-diode model) [42]	0.156	1.369	0.1
Thin film	**UF-95**	0.001	0.001	-4.83
	FS-272	0.2	0.08	-4.23
	ST40/SQ150PC (R_p-model) [42]	0.912	1.418	1.2
	ST40/ SQ150PC (two-diode model) [42]	0.853	0.709	0.9

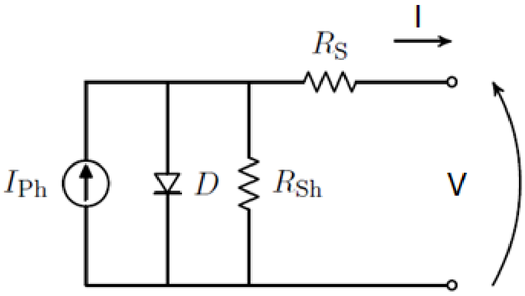
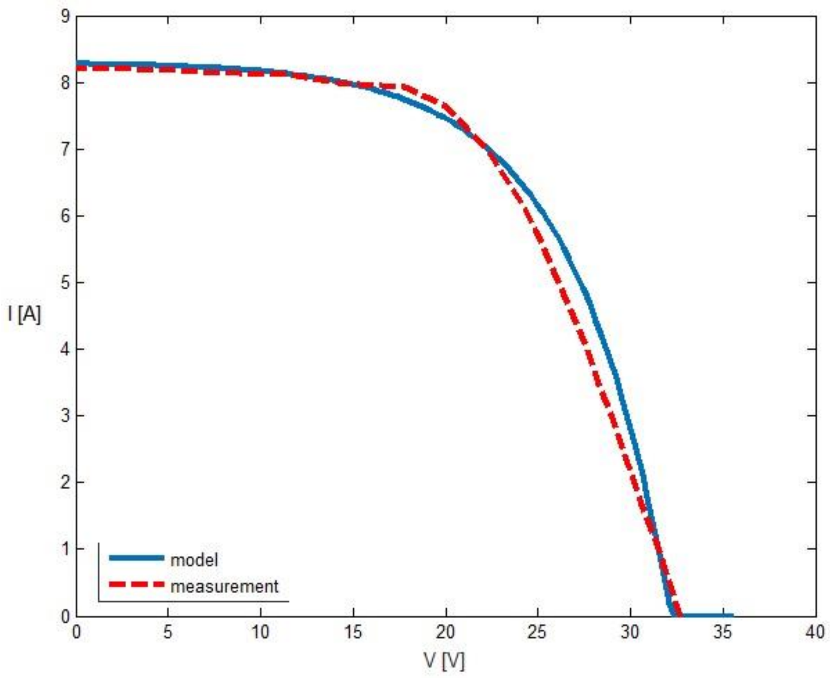


Fig.1 Solar cell equivalent circuit – five-parameters model

Fig. 2 The CdTe and CIGS PV modules used in the test

Fig. 3 Particular of the data acquisition system



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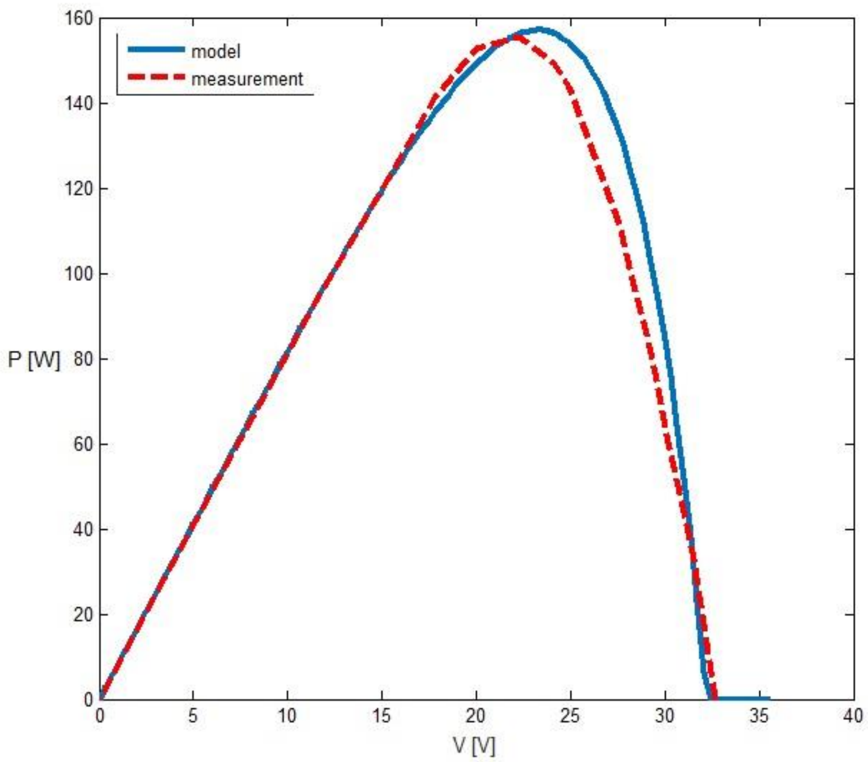
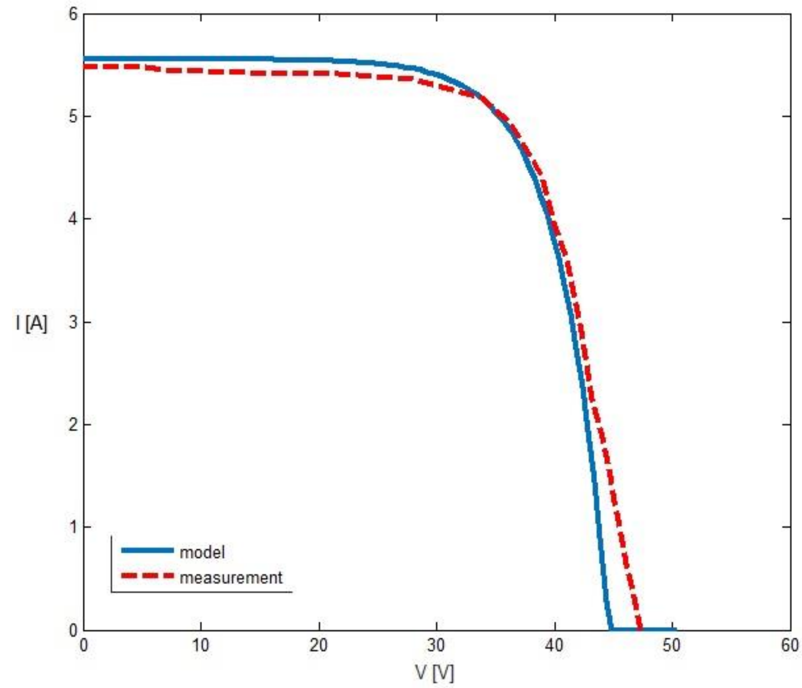


Fig.4 Characteristics for the Q.Pro module – High Irradiance (916W/m^2, T_c 57°C): (a) I-V curve; (b) P-V curve



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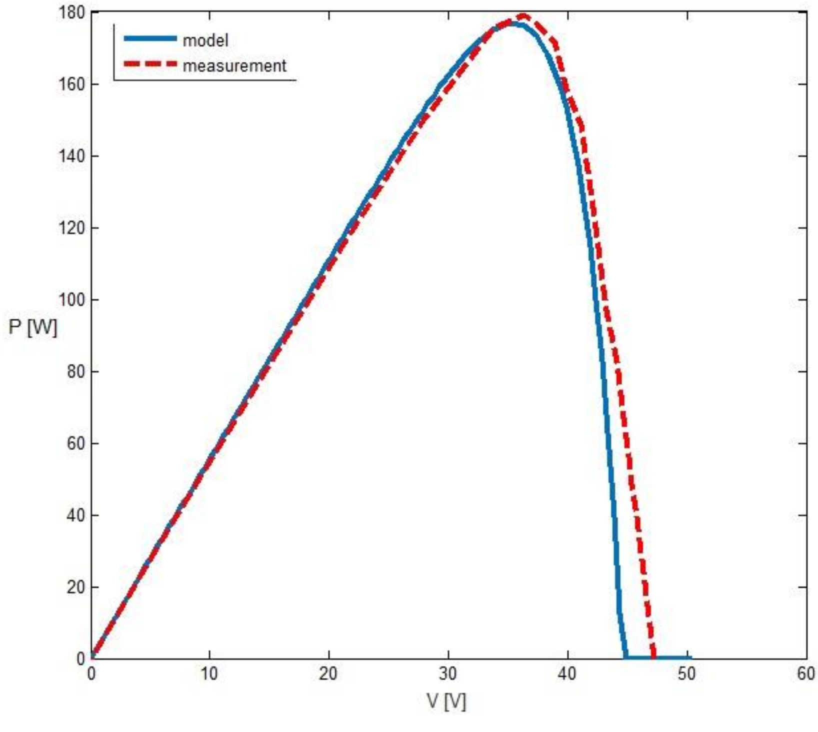
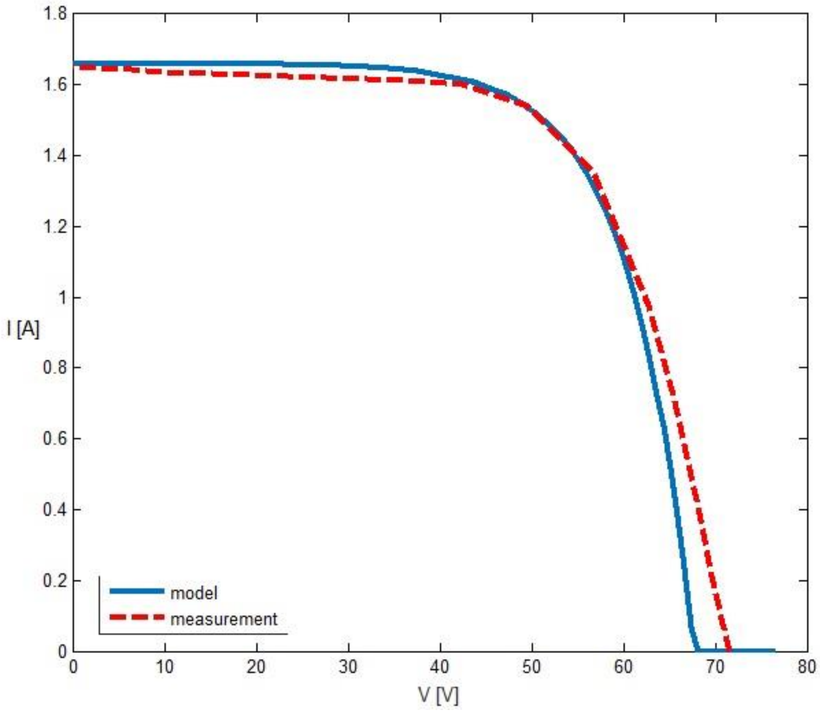


Fig.5Characteristics for the HIP215NHE5 – High Irradiance (976W/m^2, T_c 57°C):

(a) I-V curve; (b) P-V curve



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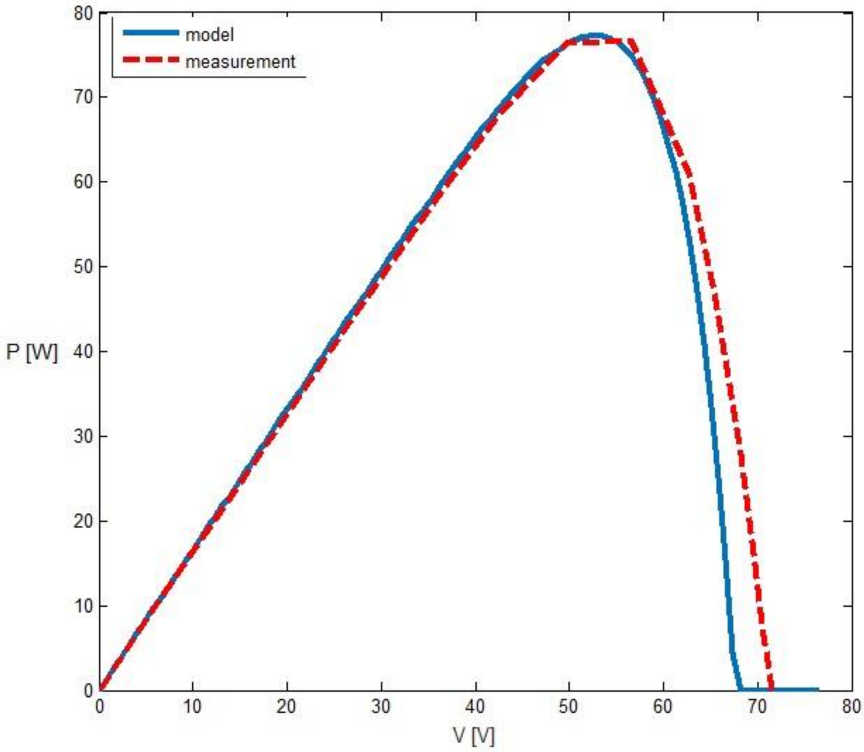
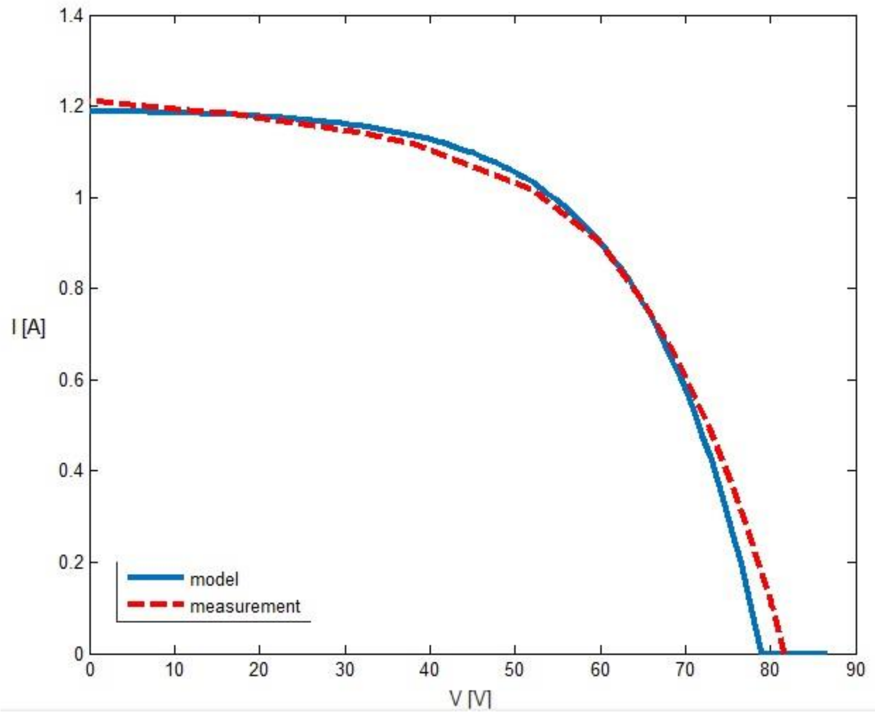


Fig.6Characteristics for the UF95– High Irradiance (970W/m^2, T_c 58°C):

(a) I-V curve; (b) P-V curve



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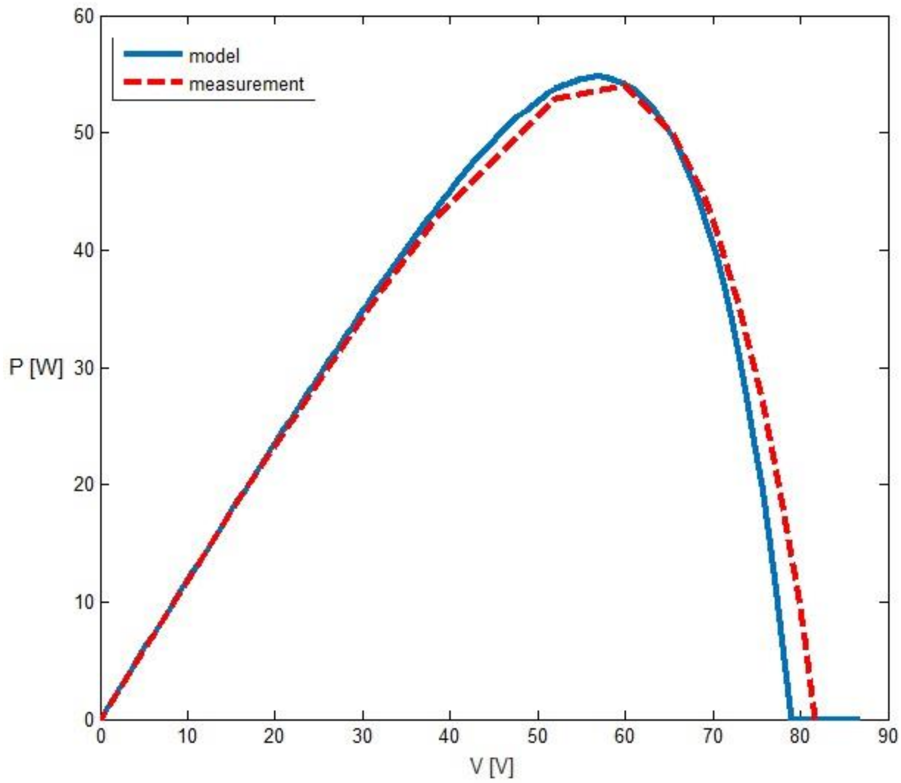
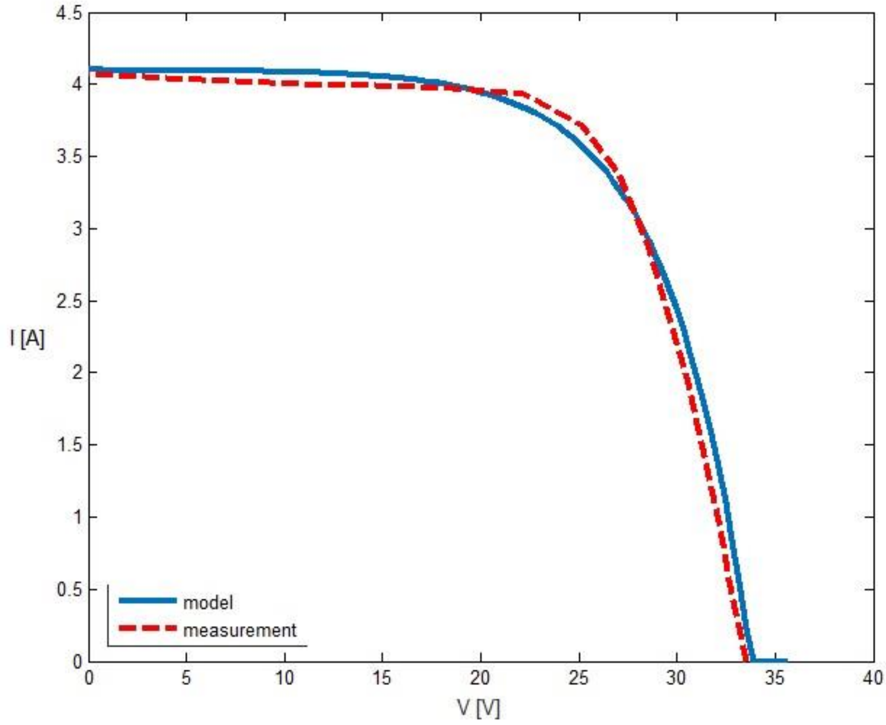


Fig.7Characteristics for the FS-272– High Irradiance (936W/m^2, T_c 56°C):

(a) I-V curve; (b) P-V curve



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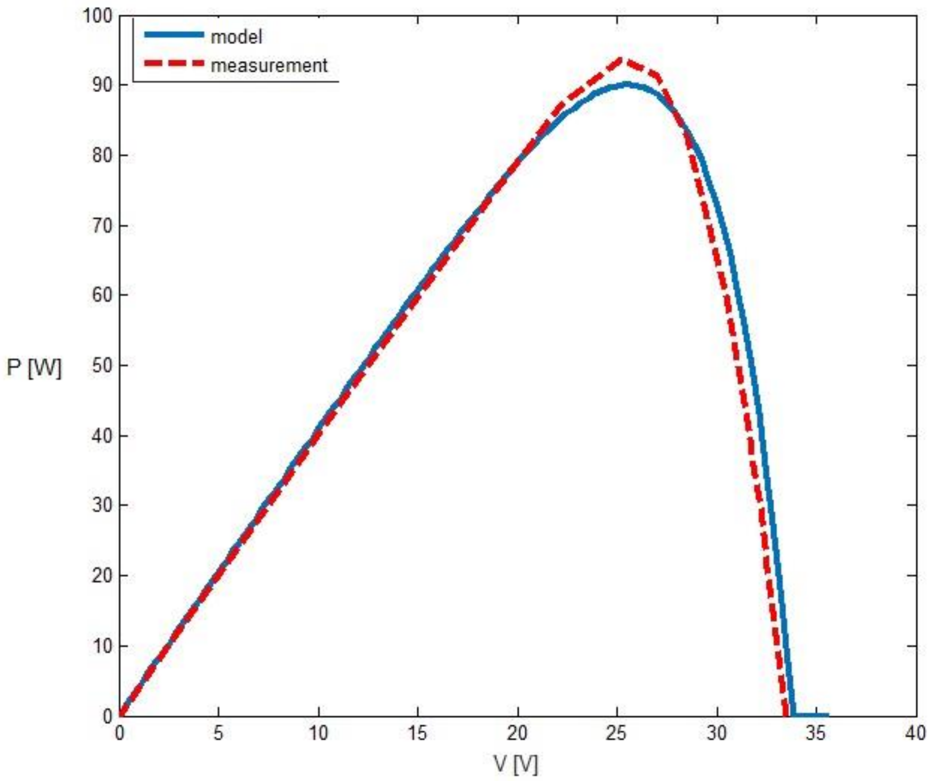
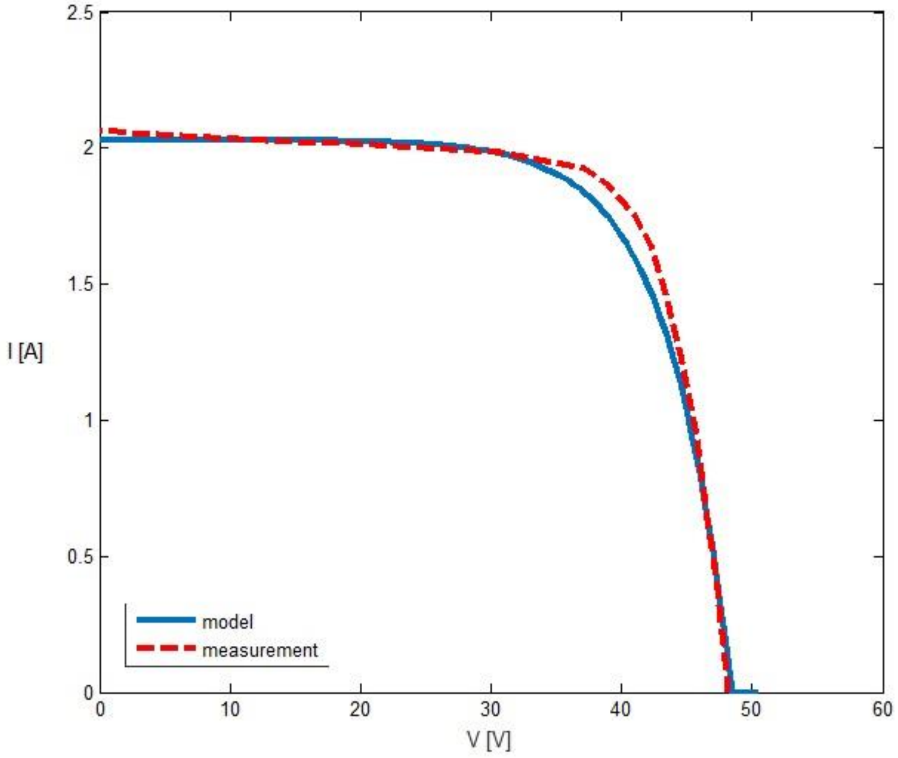


Fig.8Characteristics for the Q.Pro– Low Irradiance (446W/m^2, T_c 36°C):

(a) I-V curve; (b) P-V curve



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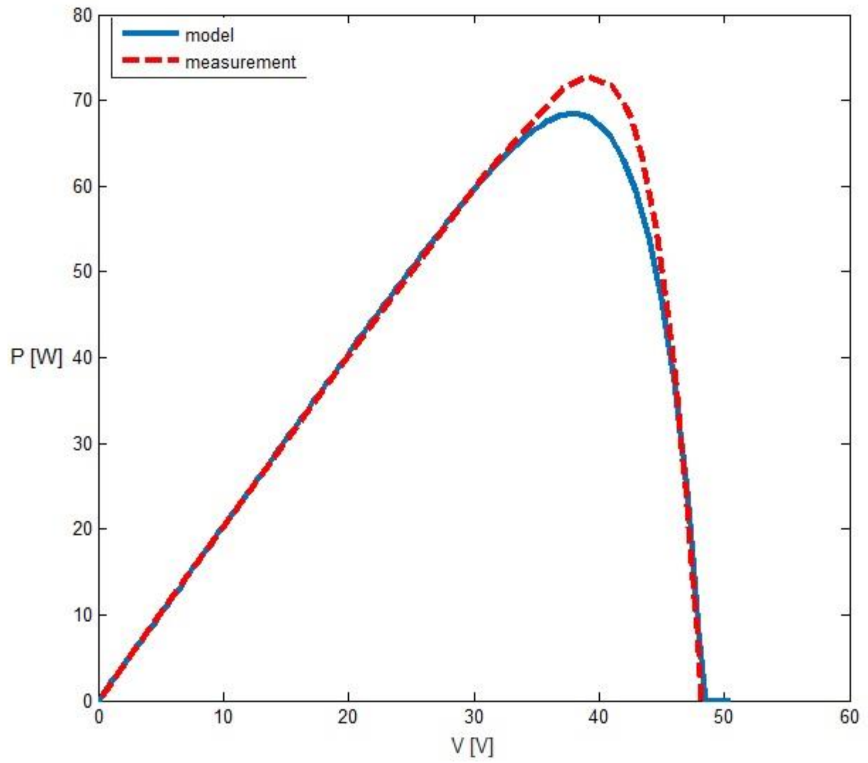
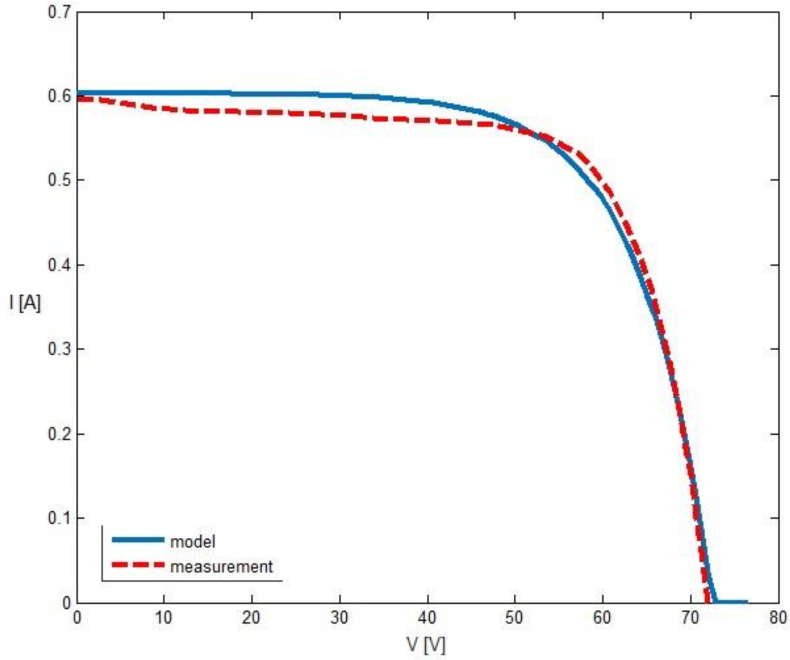


Fig.9Characteristics for the HIP215NHE5– Low Irradiance (335W/m^2, T_c 35°C):

(a) I-V curve; (b) P-V curve



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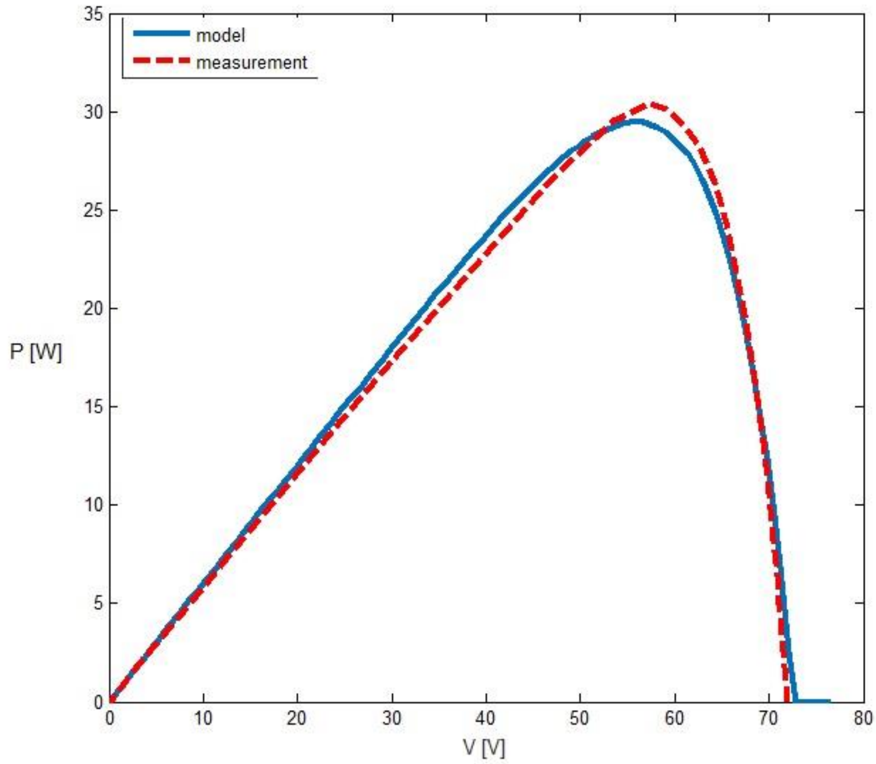
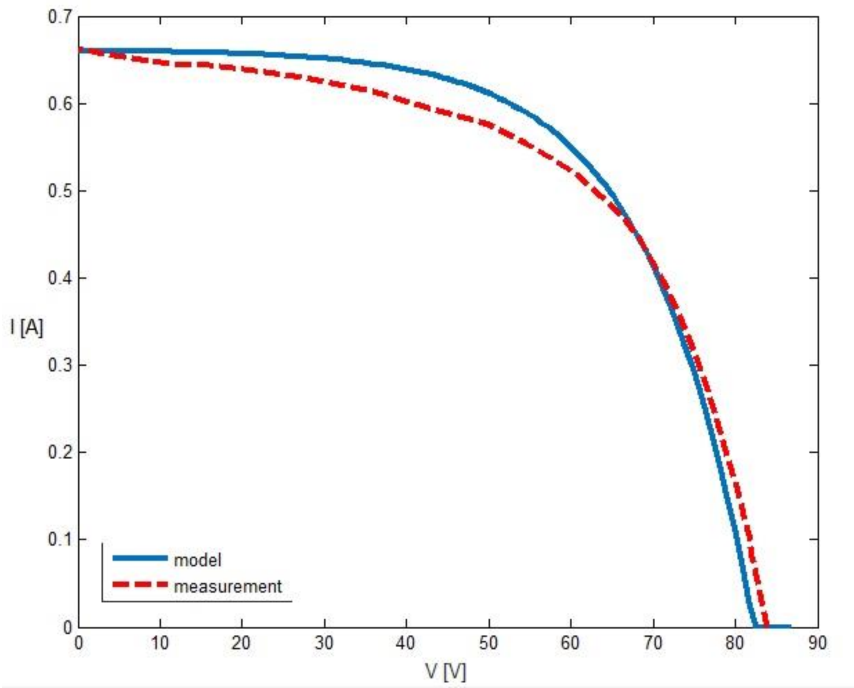


Fig.10Characteristics for the UF95– Low Irradiance (361W/m^2, T_c 38°C):

(a) I-V curve; (b) P-V curve



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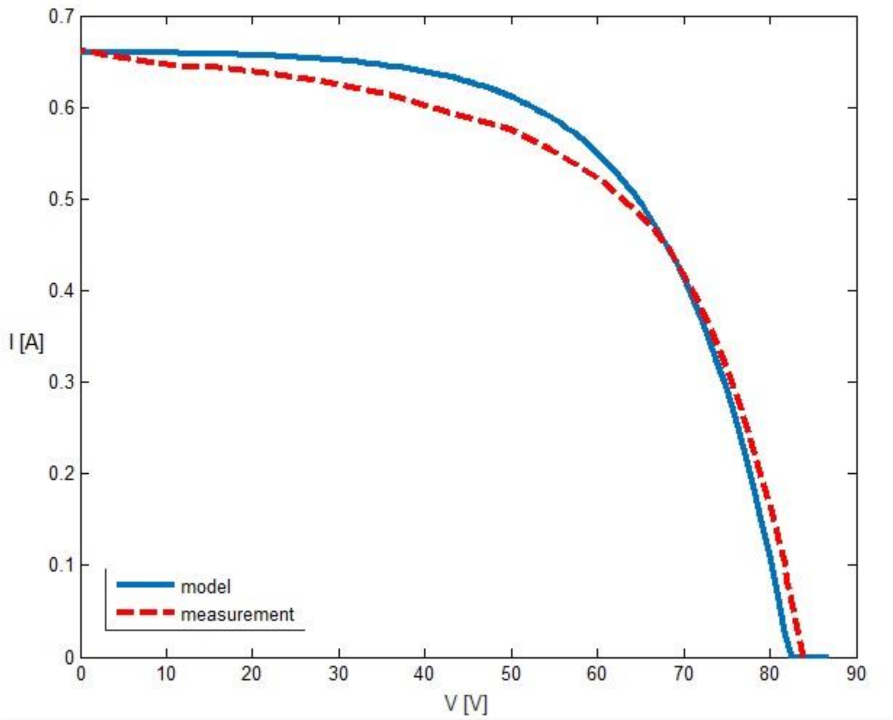

Fig.11Characteristics for the FS272– Low Irradiance (523W/m^2, T_c 41°C):

(a) I-V curve; (b) P-V curve