Models of Photovoltaic Modules with Graphical User Interface

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***Abstract*- This paper characterizes the behavior of PV modules of different technologies in different temperature and irradiance conditions with three PV models using Graphical User Interface (GUI). The outputs of the model are the I–V and P-V characteristics, as well as, the current, voltage, and Power at the maximum power point (MPP), the inputs are the irradiance intensity, the cell temperature, as well as, the type of PV module and PV model. Three of the most popular PV models have been considered in this study: One diode model, two diode model, and an explicit model; firstly, the I-V curve of three PV modules of different technologies (Si-multi-crystalline, Si-mono-crystalline, Thin film) is simulated using these three models at standard test conditions (STC), the performance of the models when subjected the temperature and irradiance variation is considered next. Finally, for experimental validation, a PV array installed on the roof -top of a building of Trieste local government in Italy was used.**

Keywords: Photovoltaic module, one diode model, two diode model, explicit model, Graphical User Interface.

I. INTRODUCTION

In the last years, the use of photovoltaic (PV) systems is increasing rapidly overall the world and photovoltaic capability is increasing from an individual system (kW) to the power plant (GW). This is the reason for the development of PV panel models useful for electrical measurement applications.

Previous researchers have utilized circuit topologies to model the I-V characteristics of PV module under different environmental conditions. The simplest approach is the single diode model (a current source in parallel to a diode) [1,2], this approach is improved by including one series resistance to the circuit, Rs [3-7]. Including an additional shunt resistance to the circuit, Rsh [8-11], the accuracy of the model is improved. A more precise model known as the two diode model [12] includes an additional diode which modeless the recombination loss in the depletion region. This type of models (implicit models) has the disadvantage of introducing a series of parameters which are difficult to obtain from solar cell's manufacturer's. For this reason, other mathematical models based on the approximations of the single diode model known as explicit models have been developed in [13-16]. These models require only three significant points of the IV curve namely: short circuit current point, open circuit voltage point, and maximum power point. Other explicit model based on the approximation on the double diode model has been developed in [17]. This model is used in this study as well as the single and the double diode models.

In this paper, a Graphical User Interface (GUI) is developed in order to simplify the comparison between the performances of different PV models, it allows the plot of I-V and P-V characteristics of PV modules of different technologies in different environmental conditions, with three PV models. The models considered in this study are: One diode, Two diode, and Explicit models; firstly, the I-V curve of three PV modules of different technologies (Si-multi-crystalline, Si-mono-crystalline, Thin film) is simulated using these three models at STC conditions. Then, the power produced by a PV array installed on the roof-top of a building of Trieste local government in Italy is modeled using these three models under different insolation level and module temperature. Finally, the simulation results obtained are compared with experimental data for cloudy and sunny days.

II. MATHEMAICAL PHOTOVOLTAIC MODELS

Several mathematical models of the I-V characteristics of PV cells/modules/arrays are available since many years in the literature. We take in this study three models: one diode model [8-11], two diode model [12], and an explicit model [17].

A. Single diode model

The equivalent circuit of the single-diode model for PV cells is shown below:

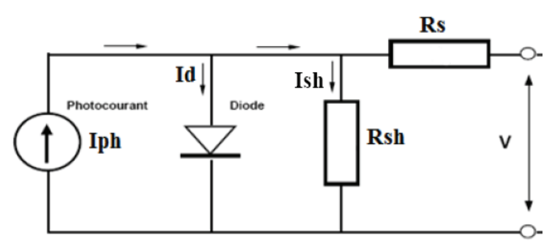

Fig. 1. Equivalent circuit of a photovoltaic cell using the single exponential model.

The general current-voltage characteristic of a PV panel based on the single exponential model is [8-11]:

$$I = I_{Ph} - I_0\left(e^{\left(\frac{V+IR_s}{ns\,Vt}\right)} - 1\right) - \left(\frac{V + IR_s}{R_{sh}}\right) \qquad (1)$$

Vt [J/C] is the thermal voltage is given by:

$$Vt = \frac{A\,K\,T_{stc}}{q} \qquad (2)$$

Where:
I_{ph} [A] is the photocurrent, I_s [A] is the cell saturation of dark current, R_{SH} [Ω] is a shunt resistance, and R_S is a series resistance, ns [ ] is the number of cells in the panel connected in series, A [ ] is an ideal factor, q (= 1.6×10^{-19} C) is an electron charge, k (= 1.38×10^{-23} J/K) is a Boltzmann's constant, T_c [°k] is the cell's working temperature.

B. Double diode model

The two-diode model is depicted in Fig. 2 [12]. The following equation describes the output current of the cell:

$$I = I_{ph} - I_{01}\left[\exp\left(\frac{V+IR_s}{A1 n_s \frac{KT}{q}}\right) - 1\right] - I_{02}\left[\exp\left(\frac{V+IR_s}{A2 n_s \frac{KT}{q}}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \quad (3)$$

Where[A] I_{01} [A] and I_{02} [A] are the reverse saturation currents of diode 1 and diode 2, respectively. A1 [ ] and A2 [ ] represent the diode ideality constants.

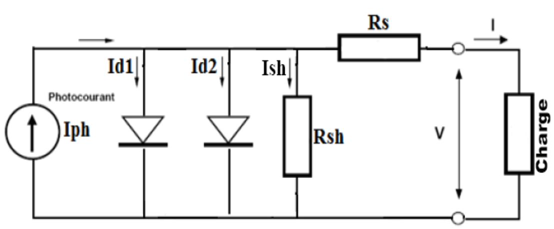

Fig. 2. Equivalent circuit of a photovoltaic cell using the double exponential model.

The influence of the environmental conditions variations on the module characteristics can be obtained from these two models. Temperature and irradiance dependence of the parameters of (1) and (3) has been expressed, and then, these equations can be completed with the new parameters resulted to obtain the IV relationship of the PV module, which takes into account the irradiance and temperature dependence.

C. Explicit model

The following model for determining the I-V characteristic of a PV module considers only parameters provided by the manufacturer's data sheet [17]:

$$I = I_L + z \cdot (25 - T_c) - \frac{e^{m \cdot [V + w \cdot (25 - T_c)]} - 1}{e^m - 1} \quad (4)$$

Where:
I [p.u.] is the per unit current referred to the short circuit current at STC Isc;
I_L [p.u.] is the per unit irradiance referred to 1.000W/m^2;
m [ ] is an exponential factor;
V [p.u.] is the per unit voltage referred to open circuit voltage at STC Voc;
w [1/°C] is the voltage-temperature coefficient referred to Voc;
z [1/°C] is the current-temperature coefficient referred to Isc;
Tc [°C] is the solar cell temperature.

The exponential factor

The exponential factor m is obtained imposing that the maximum power produced by the photovoltaic module at a given irradiance and solar cell temperature is equal to its fill factor at the same climate conditions.

The fill factor [ ] of a module working at irradiance G [W/m^2] with a temperature of the solar cells equal to T [°C] is given by [18]:

$$FF_{G,T} = FF_{0,T}.(1 - r_{s,GT}) \quad (5)$$

Where:
$FF_{0,T}$ [ ] is the normalized fill factor at the solar cell temperature T;
$r_{s,GT}$ [ ] is the normalized series resistance of the considered solar cell at irradiance G and cell temperature T.
The normalized series resistance can be calculated as [18]:

$$r_{s,GT} = \frac{I_{sc,G}}{V_{oc,T}}.R_s \quad (6)$$

Where:
$I_{SC,G}$ [A] is the module's short circuit current at irradiance G;
$V_{OC,T}$ [V] is the module's open circuit voltage at temperature T;
R_s [Ω] is the solar cell's series resistance.

These parameters can be calculated as follows [19]:

$$I_{sc,G} = \frac{G}{1.000}.I_{sc} \quad (7)$$

$$V_{oc,T} = V_{oc} + W.(T_C - 25) \quad (8)$$

$$R_s = \frac{V_{oc}}{I_{sc}}.r_s \quad (9)$$

Where:
W [V/°C] is the voltage-temperature coefficient;
r_s [ ] is the normalized solar cell's series resistance.
The normalized series resistance is given by [19]:

$$r_s = 1 - \frac{FF}{FF_{0,25}} \quad (10)$$

Where:
FF [ ] is the module's fill factor at STC;
$FF_{0,25}$ [ ] is the normalized fill factor when the solar cell temperature is 25°C.
The module's fill factor may be calculated as [18]:

$$FF = \frac{P_{n.}}{V_{oc}.I_{sc}} \quad (11)$$

Where P_n [W] is the maximum power produced by the photovoltaic module at STC.

The normalized fill factor at 25°C is given by [18]:

$$FF_{0,25} = \frac{v_{oc,25} - \ln(v_{oc,25} - 0.72)}{v_{oc,25} + 1} \tag{12}$$

Where $v_{OC,25}$ [ ] is the normalized open circuit voltage at a cell temperature of 25°C.

Finally, the normalized fill factor for a given temperature T in equation (5) corresponds to:

$$FF_{0,T} = \frac{v_{oc,T} - \ln(v_{oc,T} - 0.72)}{v_{oc,T} + 1} \tag{13}$$

Where $v_{OC,T}$ [ ] is the normalized open circuit voltage when the solar cell works at the temperature T [°C], which may be calculated as [19]:

$$v_{oc,T} = \frac{V_{oc,T}}{V_{t,T}.n_s} \tag{14}$$

Where:

$V_{t,T}$ [V] is the solar cell's thermal voltage at 25°C;

n_s [ ] is the number of cells that are connected into the photovoltaic module.

III. THE GRAPHICAL USER INTERFACE (GUI)

Based on the above equations, the three PV models have been implemented using MATLAB in order to offer a high simplicity and a wide range of the simulation of different PV models with different PV modules technologies, and under different temperature and irradiance conditions. The inputs of the GUI developed are the type of PV module and PV model as well as the irradiation intensity and cell temperature. The outputs are I-V and P-V characteristics, as well as the voltage, current, and power at the maximum power point of the PV module.

IV. MEASURED DATA

The measured data for a PV array installed on the roof -top of a building of Trieste local government in Italy [20] are used in this study to compare it with simulation results. The PV array is formed by 28 polycrystalline silicon PV modules of 115 Wp, module specifications are reported in table I. These modules are organized in 2 strings and each string is made of 14 series connected PV modules.

The data are recorded every 10 minutes for two representative days: February,2 2009 represents a cloudy winter day, and May,18 2009 represents a sunny summer day. These two days where chose since they represent different irradiance intensity, temperature, and sunny cloudy conditions.

V. RESULTS AND DESCUSSION

In this section, we present the obtained results in this work which consist on the simulated current versus voltage curves of three PV modules with different models, the analysis of the absolute error at MPP for EC-115 module under different irradiance and temperature levels, and finally the Graphical user interface developed.

A. *Simulation of I-V characteristics of PV modules*

Fig. 3 to 5 show comparison between the simulated I-V characteristic of three different modules technologies (Si-multi-crystalline, Si-mono-crystalline, Thin film) with one diode model, two diodes and explicit models at STC conditions, the key specifications of the modules are listed in Table I.

TABLE I
SPECIFICATIONS FOR THE THREE MODULES USED [20-22]

Parameter	Si-multi-crystalline EC-115 Evergreen	Si-mono-crystalline BP solar MSX-120	Thin-film Shell ST40
Isc (A)	7.26	3.87	2.68
Voc (V)	21.5	42.1	23.3
Impp (A)	6.65	3.56	2.41
Vmpp (V)	17.3	33.7	16.6
Kv (mV/°C)	-113.95	-8[illegible]	-100
Ki (mA/°C)	3.56	2.68	0.35
ns	72	72	36

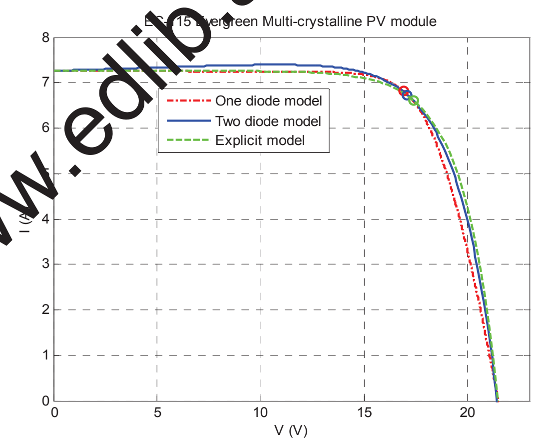

Fig. 3. I-V characteristic of EC-115 Evergreen PV module in STC.

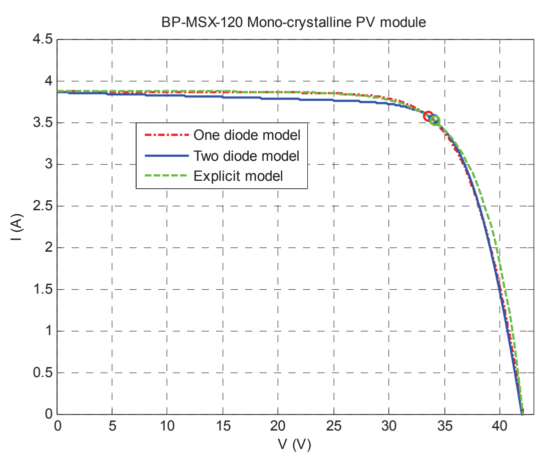

Fig. 4. I-V characteristic of BP-MSX120 PV module in STC.

 ISBN : 978-81-925233-8-5

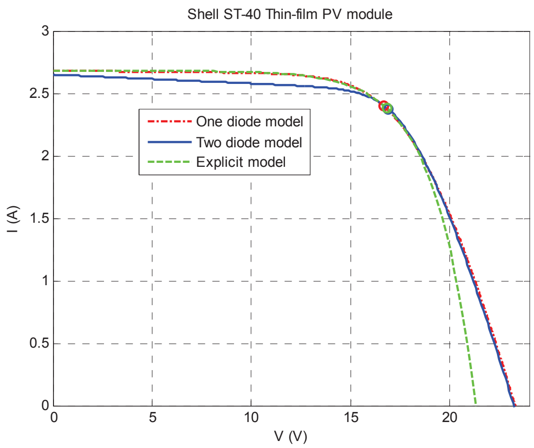

Fig. 5. I-V characteristic of Shell ST-40 PV module in STC.

It can be noted that, in the vicinity of the open circuit voltage (Voc), the curves of two diode and explicit models are very closer for multi-crystalline modules. However for thin-film and mono-crystalline modules, we show a good correspondence between single and double diode models. In addition, explicit model shows departure from one diode and two diode models for thin-film module at Voc, suggesting that the explicit model is inadequate when dealing with thin-film technology. In other hand, in the vicinity of the short circuit current (Isc), it can be observed that one diode and explicit models have similar characteristics for all the three modules tested, but two diode model exhibits a small deviation from other two models.

TABLE II
ABSOLUTE ERRORS ON THE I_{SC}, V_{OC}, and P_{MP} OF THREE MODELS AT STC CONDITIONS FOR THE THREE MODULES

		Modules		
		Ec-115	MSX-120	ST-40
Error for 1 diode model	E_{Isc} (A)	0	0	0
	E_{Voc} (V)	0	0	0
	E_{Pmp} (W)	0.[illegible]2	0.0098	0.004
Error for 2 diode model	E_{Isc} (A)	[illegible]	0.01	0.03
	E_{Voc} (V)	0.1	0.1	0.1
	E_{Pmp} (W)	0.11	0.09	0.082
Error for explicit model	E_{Isc} (A)	0	0	0
	E_{Voc} (V)	0	0	2
	E_{Pmp} (W)	0.002	0.001	0.004

Table II provides the absolute error of short circuit current, open circuit voltage, and maximum power between the three models at STC for three different modules. The absolute error is defined as the difference between simulated and measured values. It can be observed a good estimation of the short circuit current and open circuit voltage for the three modules with different models, except for thin-film module with explicit model, it has a significant error at the open circuit voltage. However, at the maximum power point (Mpp), the best accuracy is obtained from one diode and explicit models for thin film technologies. For mono-crystalline and multi-crystalline modules, more accurate results are obtained with explicit model. Furthermore, for multi-crystalline modules, two diode model is more accurate than the one diode model.

B. Analysis of absolute error at MPP for different environmental conditions.

In order to show the effectiveness of the models for different environmental conditions, comparison between measured power produced by PV array mentioned above and simulated results obtained with one diode model, two diode, and explicit models are carried out.

For easy comparison, the absolute error values of output power for various irradiation intensity and temperature are calculated and depicted in tables III and IV. From these tables, it can be noted that: at low temperature, more accurate results are obtained with two diode model. Furthermore, one diode and explicit models have approximately equivalent performance. However, at high temperature, the absolute error from two diode model increases significantly as shown in table IV. The best accuracy results in this case are obtained with one diode model.

TABLE III
ABSOLUTE ERRORS BETWEEN MEASURED AND SIMULATED POWER PRODUCED BY PV ARRAY WITH ONE DIODE,TWO DIODE, AND EXPLICIT MODELS AT LOW TEMPERTURE

G (W/m2)	Tc (°C)	One diode model	Two diode Model	Explicit model
		E_P (W)	E_P (W)	E_P (W)
44	8.4	16.32	11.61	15.33
52	7.1	71.92	25.04	39.56
99	8.8	69.02	4.84	57.34
164	10.9	108.61	9.23	85.59
197	11.4	120.24	23.61	92.21
380	13.9	150	80	120

TABLE IV
ABSOLUTE ERRORS BETWEEN MEASURED AND SIMULATED POWER PRODUCED BY PV ARRAY WITH ONE DIODE,TWO DIODE, AND EXPLICIT MODELS AT HIGH TEMPERTURE

G (W/m2)	Tc (°C)	One diode model	Two diode model	Explicit model
		E_P (W)	E_P (W)	E_P (W)
590	42.9	120	190	190
703	29	10	30	40
750	31.1	20	70	80
805	30.7	10	100	60
815	53.4	100	720	160
840	50.7	130	640	190
868	56	120	870	170

C. The Graphical User Interface developed

The GUI represented in fig.6 allows the user to plot the I-V and P-V characteristics of different PV modules with different PV models and under different environmental conditions, also

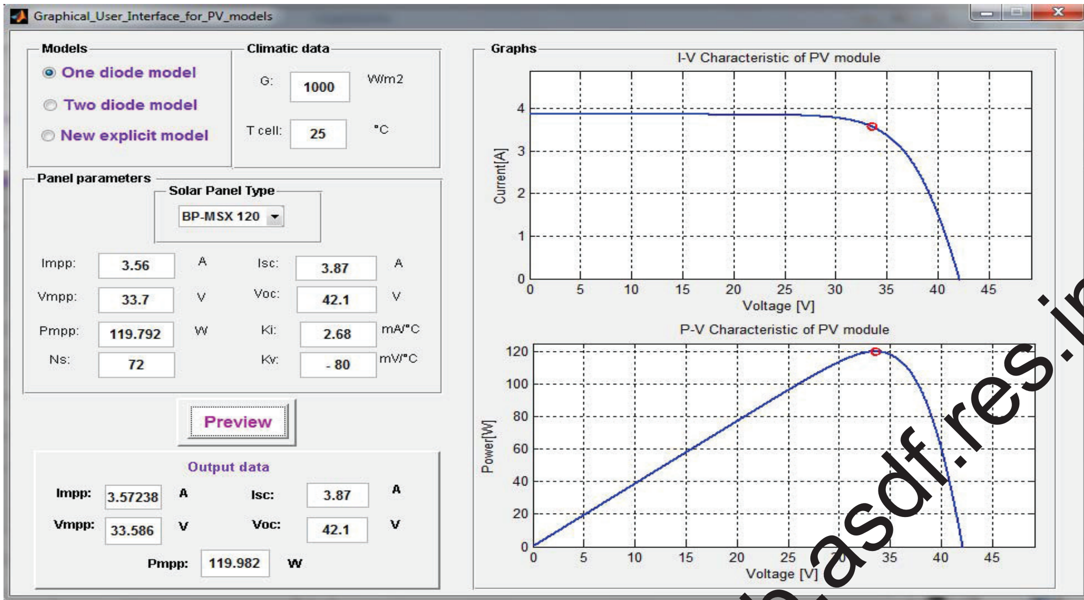

Fig. 6. The Graphical User Interface for PV models.

it allows him to know the current, voltage, and power values at the short circuit current point, open circuit voltage point, and maximum power point. Firstly, the user chooses the PV model used from the three PV models implemented, the irradiance intensity (W/m2), as well as the cell temperature (°C). The type of PV module has been chosen next, and the specifications of the module are displayed. Finally, the button "Preview" allows the user to show the I-V and P-V characteristics as well as current, voltage, and power at the short circuit current point, open circuit voltage point, and maximum power point.

VI. CONCLUSION

In this paper, a comparison between performances of one diode, two diode, and new explicit models is presented using Graphical User Interface. The developed GUI allows the user to observe the characteristics of the PV modules from different technologies(Si-multi-crystalline, Si-mono-crystalline, Thin film) in various environmental conditions, and with three models. Firstly, The I-V curves of three different modules are simulated using these models at STC conditions. Then, the power produced by a PV array installed on the roof -top of a building of Trieste local government in Italy is modeled, the simulation results obtained are compared with experimental data for cloudy and sunny days. Finally, the developed GUI is presented.

Acknowledgment

Authors wish to thank the municipality of Trieste and Mr. F. Romeo for providing the experimental data of climate and electrical signals. Particular thanks also to Mr. L. Farneti for his efforts in making possible the remote access of the electrical and climate data at the University of Trieste. Also thanks to Mr. A. Massi Pavan for providing the means and the computers facilities for performing the present work.

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