A Simplified Model of Photovoltaic Panel

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***Abstract*—As well known, the market of PV systems is having a great development nowadays. In this process both companies and governments require to evaluate the projects of PV plants both in terms of revenue and quality. Therefore accurate tools for predicting their performances are becoming more and more important. The accuracy of the estimation is key for photovoltaic applications since this technology is characterized by quite low efficiency and high fixed costs. In this scenario, it is extremely important to develop models of each component of the system in order to evaluate the PV plant behavior in any working condition. In this paper a flexible model of PV module suitable for off-line and on-line simulation will be presented and discussed. It will be shown that beside its simplicity, the accuracy is very good. Furthermore its parameters can be easily measured or estimated from the rated values.**

Keywords- Photovoltaic panels; modelling; system efficiency; maintanence.

I. INTRODUCTION

In the last decades, in order to favorite the replacement of traditional energy sources with renewable and less polluting ones, many governments have introduced incentive pay systems. This policy has been effective in helping the diffusion of new energy sources [1]. One of the most promising is for sure the solar light: it is quite easy to exploit and the required plants can be very well integrated in the urban territories, thus reducing the environmental impact.

Unfortunately the efficiency of the photovoltaic technology is quite low, and this reduces its competitiveness with respect to the traditional energy sources. Until now it has been compensated by the incentives issued by the government. In the last years the amount of these incentives has been reduced, thus highlighting the problem of the efficiency of the whole system. This aspect becomes even more important when big solar plants are taken into account. In fact, in this case the investors require a punctual evaluation of cost and earnings. It requires to simulate the behavior of the whole system in order to evaluate both the energy production and the maintenance costs.

Therefore, it is necessary to have quite accurate models for every component of the system; they have to be as simple as possible and suitable for the integration with the other parts. Let us consider in particular the PV panels. Their models are key both for predicting the energy production and the cost of the maintenance. Furthermore, they shall also provide indication about the degradation of the PV panel in order to precisely predict its actual behavior. Several model of PV panels can be found [2]-[16] in literature. Most of them are quite accurate but they suffer from some limitations which makes them not completely suitable for the purpose. First of all, their parameters cannot be easily extracted from the rated values but a set of measurements is needed. Therefore, they are seldom available during the economical evaluation of a new plant. The high number of parameters is a sign of the complexity of the model. This complexity can be attributed to the attempt in obtaining a high accuracy in the whole range of operating currents and voltages. However, in many cases and in particular for an economic analysis, it is sufficient to have a good accuracy near the Maximum Power Point (MPP) where the panels are supposed to operate most of the time. This approach leads to a significant simplification of the problem.

In this paper a simple yet accurate model of PV panel will be presented. All of the model parameters can be identified from the rated parameters. It is suitable for the simulations to be performed during the business planning and design stage. An experimental validation of the model will also be provided.

II. A SIMPLIFIED MODEL OF PV PANEL

In literature different models of PV cells can be found. Many of them are characterized by a large number of exponential terms. Moreover their characterization requires following an onerous procedure and often the achieved accuracy does not justify the complexity.

An excellent compromise is represented by the two-diode model [4] (three-diode model for polycrystalline photovoltaic modules [5]). It ensures a fine matching between the estimated and the measured electric characteristic.

By considering that the two/three exponentials models do not usually take into account several effects which are relevant in some particular conditions (e.g. the spectral content of the solar radiation [6], cells temperature gradients [7], …), their accuracy can be comparable to that of simpler models. Moreover one of the exponential terms usually produces significant effects only when the radiation and the voltage are low [8]. Starting from these assumptions it can be concluded that the single diode model represents a good compromise between accuracy and simplicity [9]:

$$I = I_{ph} - I_s\left(e^{\frac{V+R_s I}{V_T}} - 1\right) - \frac{V + R_s I}{R_{sh}} \tag{1}$$

The single diode model requires the knowledge of five parameters; several procedures to evaluate them starting from

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the datasheet values ([10], [11] and [12]) or from experimental measurements ([4] and [8]) have been developed.

Unfortunately, the explicit expression of the voltage V and of the current I does not exist. For this reason, several authors have proposed some other simplifications: in fact, by neglecting the shunt resistance R_{sh} the equation can be solved in closed form and the voltage can be expressed as a function of the current; vice versa, by neglecting the series resistance R_s the current can be expressed as an analytic function of the voltage.

$R_{sh}\rightarrow\infty$ is a very common assumption; it has been demonstrated that it does not produce relevant effects in working points close to the MPP (where the PV module usually operates) [13] and a good matching with the actual *V-I* characteristic can be anyway reached by opportunely tuning the value of the thermal voltage V_T [14]. On the contrary R_s cannot be usually neglected since little variations of its value may have relevant effects around the MPP [13]. However, in some conditions, e.g. when the equivalent resistance of the connection cables is high if compared to R_s, the R_s=0 assumption does not introduce appreciable errors on the simulation of the whole system [3] [11].

By considering these statements, a good accuracy can be preserved by neglecting just R_{sh} (Figure 1), and the model can be written as follows:

$$V = V_T \ln\left(1+\frac{I_{ph}-I}{I_s}\right) - R_s I \tag{2}$$

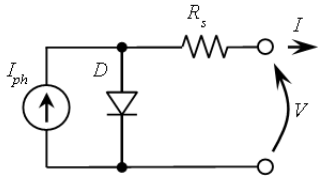

Figure 1. Single diode equivalent circuit

Usually, it is preferable to replace the photocurrent I_{ph} and the reverse saturation current I_s with the parameters that are commonly provided by manufacturers or that can be easily estimated from the *V-I* characteristic. One of these parameters is the open circuit voltage V_{oc} which can be used to obtain I_s. In fact the following equation can be written:

$$V_{oc} = V\big|_{I=0} = V_T \ln\left(1+\frac{I_{ph}}{I_s}\right) \quad \rightarrow \quad I_s = \frac{I_{ph}}{e^{\frac{V_{oc}}{V_T}}-1} \tag{3}$$

Since $I_{sc} >> I_s$ and the voltage across the series resistance R_s is small, it is possible to assume that the short circuit current I_{sc} is approximately equal to the photocurrent [13]. By considering the last assumptions, (2) becomes:

$$V = V_T \ln\left[1+\left(1-\frac{I}{I_{sc}}\right)\left(e^{\frac{V_{oc}}{V_T}}-1\right)\right] - R_s I \tag{4}$$

(4) can also be written as:

$$V = V_{oc} + V_T \ln\left[e^{-\frac{V_{oc}}{V_T}} + \left(1-\frac{I}{I_{sc}}\right)\left(1-e^{-\frac{V_{oc}}{V_T}}\right)\right] - R_s I \tag{5}$$

Since normally $e^{-\frac{V_{oc}}{V_T}} << 1$, (5) can be well approximated by the following expression:

$$V = V_{oc} + V_T \ln\left(1-\frac{I}{I_{sc}}\right) - R_s I \tag{6}$$

This new equation provides a simpler model for photovoltaic modules, which practically has the same behaviour of the traditional single exponential formulation. In Figure 2 the equivalent circuit of (6) is depicted: in this case, the diode is characterized by a thermal voltage equal to V_T and a reverse saturation current equal to I_{sc}.

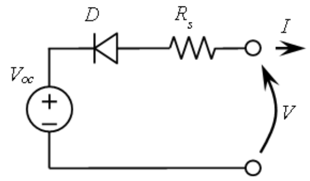

Figure 2. Equivalent electric circuit of the proposed model

Thanks to the developed model, the knowledge of the MPP voltage V_{mp} and current I_{mp}, of the short circuit current and of the open circuit voltage (for a given value of temperature and radiation) permits to analytically calculate both the thermal voltage and the series resistance. In fact, by solving the following system of two equations, the values of V_T and R_s can be computed:

$$\begin{cases} V_{mp} = V_{oc} + V_T \ln\left(1-\dfrac{I_{mp}}{I_{sc}}\right) - R_s I_{mp} \\ \left.\dfrac{d(VI)}{dI}\right|_{I=I_{mp}} = V_{mp} + \dfrac{V_T I_{mp}}{I_{mp}-I_{sc}} - R_s I_{mp} = 0 \end{cases} \tag{7}$$

The first equation of (7) imposes that the voltage-current characteristic includes the maximum power point; the second one imposes that the derivative of the electric power is null in that point. The solution is:

$$\begin{cases} V_T = \dfrac{\left(2V_{mp}-V_{oc}\right)\left(I_{sc}-I_{mp}\right)}{I_{mp}+\left(I_{sc}-I_{mp}\right)\ln\left(1-\dfrac{I_{mp}}{I_{sc}}\right)} \\ R_s = \dfrac{V_{mp}}{I_{mp}} - \dfrac{2V_{mp}-V_{oc}}{I_{mp}+\left(I_{sc}-I_{mp}\right)\ln\left(1-\dfrac{I_{mp}}{I_{sc}}\right)} \end{cases} \tag{8}$$

Therefore, thanks to the measurement of three salient points of the *V-I* characteristic (open-circuit, short-circuit and MPP) for a known value of temperature and radiation it is possible to analytically calculate all the parameters of the proposed PV model. In contrast, the traditional formulation requires numerical procedures for their evaluation [10][12].

This feature highly simplifies the characterization: the parameters of the model can be simply obtained using the values listed in the technical datasheets of the PV panel. In fact, the manufacturers usually provide the open circuit voltage V_{oc0}, the short circuit current I_{sc0}, the voltage V_{mp0} and current I_{mp0} of the MPP, all measured in Standard Test Conditions[1] (STC).

Since the STC thermal voltage V_{T0} and the series resistance R_s can be calculated, (6) provides an estimation of the whole electric characteristic. When different values of solar radiation intensity G and cell temperature T_c have to be taken into account, the changes in the open circuit voltage V_{oc}, the short circuit current I_{sc} and the thermal voltage V_T have to be considered. A method to estimate the variations of these quantities is provided by the following formulas [17]:

$$I_{sc}\left(G,T_c\right)=I_{sc0}\frac{G}{G_0}\left[1+\alpha\left(T_c-T_0\right)\right] \tag{9}$$

$$V_{oc}\left(G,T_c\right)=V_{oc0}\left[1+\beta\left(T_c-T_0\right)\right]+V_{T0}\ln\left(\frac{G}{G_0}\right) \tag{10}$$

$$V_T\left(T_c\right)=V_{T0}\frac{T_c}{T_0} \tag{11}$$

While these parameters depend on the environmental conditions, the series resistance R_s is not significantly influenced by both solar radiation and cells temperature [10] so it is considered as a constant.

The proposed novel formulation guarantees the same accuracy of the traditional model, despite of significant improvements in the simplicity. In fact the introduced approximations reduce the computational requirements allowing a full analytical characterization of the model.

III. Measurement Setup

A measurement setup for the testing of PV panels has been developed. The system permits to experimentally evaluate their *V-I* characteristic. Figure 3 reports the measurement system.

The sampling of the PV voltage and current has been performed with a NI 9215 board, which includes 4 analog inputs with a maximum sampling frequency of 100 kSamples/s and a 16 bit resolution.

The formulation of the model requires the estimation of two environmental quantities:

- the solar radiation: it has been measured with a CMP 21 global radiometer (class 1) which has been positioned with the same orientation of the PV module under test;
- the cell temperature of each PV panel: it has been measured by using a PT100 placed on the rear surface.

These quantities have been acquired with 16 bit resolution.

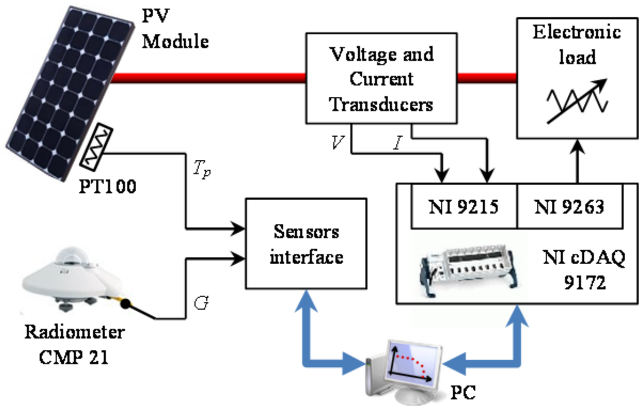

Figure 3. Measurement system.

Both electrical and environmental measurements have been managed by a Virtual Instrument (VI), developed in NI LabVIEW, which also controls the electronic load allowing to acquire the whole *V-I* characteristic of the PV module.

IV. Experimental Validation

The proposed model has been verified by analyzing two PV panels whose rated parameters have been reported in TABLE I. Both of them have been built using monocrystalline technology.

TABLE I. DATASHEET PARAMETERS OF THE TWO PANELS.

	PV1-180W	PV2 - 70W
V_{mp0}	36.80 V	17.50 V
I_{mp0}	4.90 A	4.00 A
V_{oc0}	44.20 V	22.20 V
I_{sc0}	5.35 A	4.27 A
α	0.05%	not reported
β	-0.34%	-0.41%

Thanks to (8) and using the parameters provided by the manufacturers, the thermal voltage and the series resistance have been computed. In TABLE II the values obtained from the rated parameters are listed.

TABLE II. VALUES OF V_{T0} AND R_S.

	PV1-180W	PV2 - 70W
V_{T0}	3.49 V	1.06 V
R_s	-0.26 Ω	0.44 Ω

Now, by considering the proposed model and the computed parameters, the *V-I* curves of the two panels can be drawn. As expected, Figure 4 shows that the MPP values of both the PV panels, computed by means of the proposed model, correspond to their rated values.

[1] Light radiation intensity G_0 = 1000 W/m^2, PV cell temperature T_c = 298.15 K and air mass coefficient AM = 1.5.

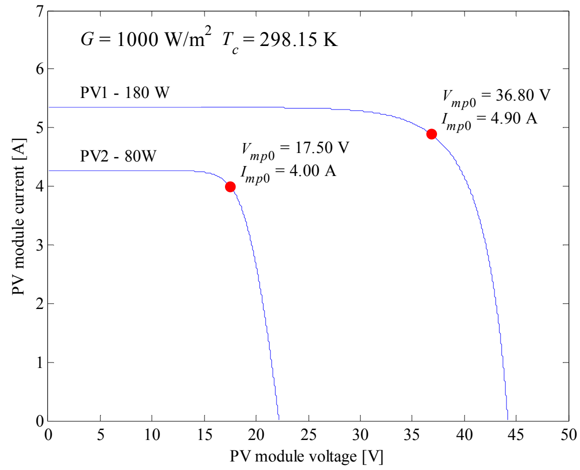

Figure 4. *V-I* curves of the PV modules computed by using the proposed model.

It is clear that the accuracy of the model strongly depends on that of the rated parameters. In order to accurately predict the behaviour of a PV panel the uncertainty of these parameters should be considered as well as the degradations due to the ageing [18].

If a better modelling is required, a characterization of the PV panels has to be performed. In order to experimentally evaluate the parameters of the proposed model, a measurement campaign has been performed by using the measurement setup described in Section III.

For both of the tested PV modules, 300 *V-I* curves have been acquired and 100 of them, randomly chosen, have been used for the identification of the parameters. Through the employment of the Matlab/Curve Fitting Toolbox®, it has been found that the best matching between the measured characteristics and the model is obtained with the parameters shown in TABLE III.

TABLE III. VALUES OF THE PARAMETERS COMPUTED FROM THE EXPERIMENTAL DATA.

	PV1-180W	PV2 - 70W
V_{mp0}	35.03 V	16.48 V
I_{mp0}	4.84 A	4.00 A
I_{sc0}	5.21 A	4.44 A
V_{oc0}	44.18 V	22.68 V
α	0.15%	0.09%
β	-0.29%	-0.35%
V_{T0}	2.44 V	1.50 V
R_s	0.55 Ω	0.68 Ω

The comparison of the model parameters obtained from the measurement with those computed starting from the rated values shows that the differences are relevant, especially for the thermal voltages and the series resistances. In Figure 5, a comparison between the *V-I* curves obtained by means of the proposed model (using both the rated parameters and the measurement results) and the experimental *V-I* characteristic of panel PV1 is reported. In particular it can be noticed that employing the model parameters computed from the rated values the error is much higher.

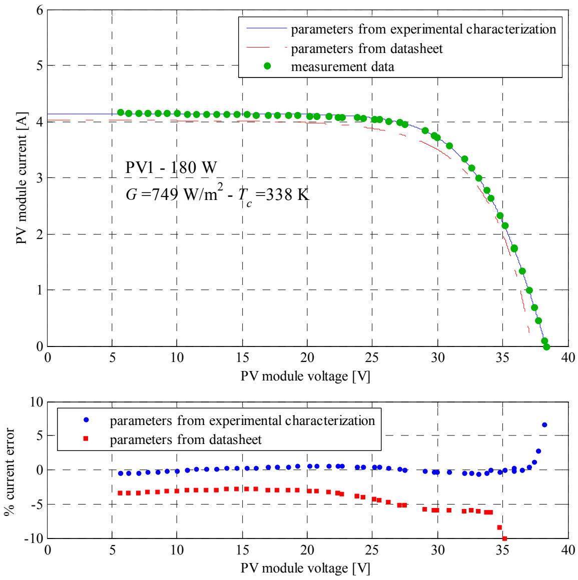

Figure 5. Comparison between *V-I* characteristics obtained with different methods.

Moreover, the error in estimating the generated power at MPP is -5.91% when the parameters of the proposed model have been computed using the rated values. It reduces to -0.24% if the experimental data are employed for their identification.

V. IMPACT OF TEMPERATURE AND RADIATION UNCERTAINTIES

The experimental activity have shown that, having properly tuned the relevant parameters, the proposed model closely matches the measured *V-I* characteristics of a PV panel, in particular near the MPP. Therefore, it can be concluded that the definitional uncertainty related to the employment of said model is pretty low.

The proposed model can be employed to estimate the power generated by a panel for a known solar radiation and temperature. In many cases, for example during the economical evaluation of a new PV plant, it is interesting to acquire the solar radiation and the temperature in a particular area for a certain period in order to estimate the amount of energy that will be generated if a PV panel is installed there. The panel temperature T can be obtained using a proper thermal model [15], [16]. In this case, it is important to understand how the uncertainties related to the measurement of the solar radiation and to the estimation of the panel temperature affect the predicted value of generated power, having supposed that the operation is at the MPP. This analysis has been carried out adopting a Monte Carlo approach. The measurement of the solar radiation G_{est} and the estimation of the panel temperature T_{est} are random variables; Gaussian, uncorrelated probability distribution functions have been considered for the sake of simplicity. Their expectations $E(G_{est})$ and $E(T_{est})$ represent the working condition of the panel; $E(T_{est})$ has been swept form 0 °C to 80 °C (with steps of 10° C), while values of $E(G_{est})$ ranging from 100 W/m^2 to 1000 W/m^2 (with increments of 100 W/ m^2) have been taken into account. The standard deviation stdev(G_{est}) is due to the uncertainty of the radiometer. Values of 1%, 2.5% and 5% have been considered, which are half of the typical expanded uncertainties of radiometers. The standard deviation stdev(T_{est}) takes into account the uncertainty related to the estimation of the panel temperature; expanded uncertainty values of 2 °C, 4 °C and 10 °C with a coverage factor of two have been employed. Then, the probability density functions of the voltage, current and power at MPP have been estimated through a Monte Carlo calculation in every operating condition; 10^5 trials have been executed in each working point. The uncertainties have been computed as the semiamplitude of the 95% coverage interval. Some results are shown in Figure 6-8 which reports the maximum value of expanded uncertainty computed in the considered working conditions as a function of the uncertainties of the radiometer and of the estimated panel temperature.

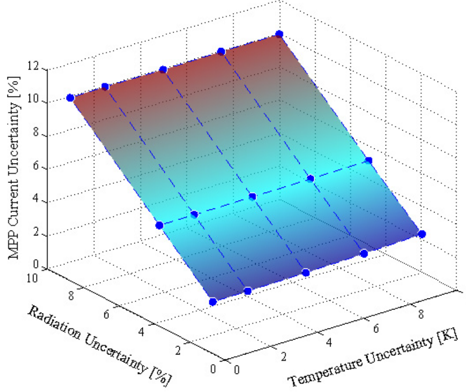

Figure 6. Uncertainty of the estimated current at MPP.

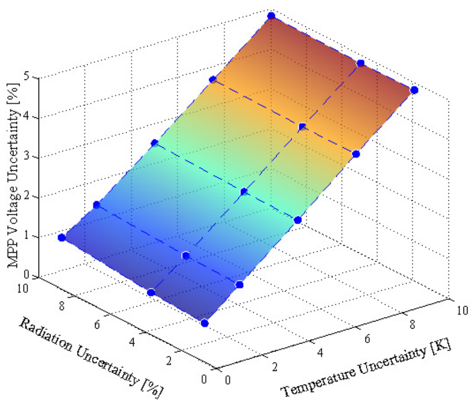

Figure 7. Uncertainty of the estimated voltage at MPP.

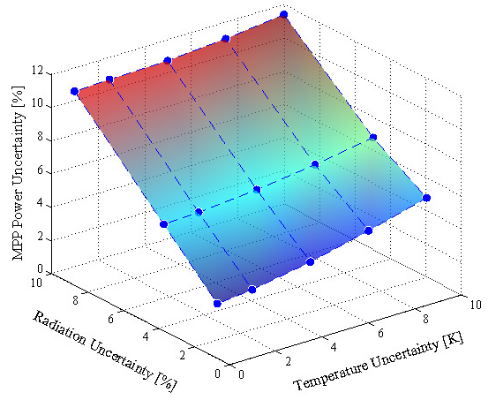

Figure 8. Uncertainty of the estimated power output at MPP.

The results show that the measurement uncertainty of the solar radiation has in general a heavier effect on the estimation of the current at MPP than that related to the estimation of the panel temperature. This is not a surprise since the MPP current strongly depends on the radiation, while its sensitivity to the temperature is weaker. Vice versa, the uncertainty due to the radiometer has just a slight effect on the evaluation of the MPP voltage, while the uncertainty related to the estimated panel temperature has a greater impact. In fact it is well known that the MPP voltage is heavily affected by the temperature, but it is much less sensitive to the amount of solar radiation. Finally, Figure 8 clearly shows that in general the uncertainty of the power output at MPP is mainly due to the radiometer, where the impact of the estimated panel temperature is appreciably lower. Therefore, when the aim is the prediction of the energy production, the panel temperature can be estimated through inexpensive instrumentation and rough thermal modelling, unless a very accurate (and expensive) radiometer is employed.

VI. CONCLUSION

In this paper a new, simple model of photovoltaic panel has been presented. It can be represented as an electrical network constituted by the series connection between a diode, a resistor and a voltage generator. The main advantage relies in the fact that the parameters can be easily obtained from the values usually provided by the manufacturer, rather than properly measured when higher precision is required. Beside its simplicity, the model has proven to be quite accurate, especially near the maximum power point, where the panel is usually supposed to operate. The proposed model can be employed to predict the maximum power generated by PV panel for a given value of temperature and radiation. In this case it is very important to analyse the effect of their uncertainties on the estimated power output. Following a Monte Carlo approach, it has been shown that when the task is predicting the power output, the uncertainty due to the radiometer has a great impact, where that related to the estimation of the cell temperature has a much weaker effect. Therefore, in most cases simple thermal models and cheap temperature transducers can be employed.

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