Simplified Model of a Photovoltaic Module

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Abstract – **The cost and the performance of PV plants strongly depends on modules. However, the electrical parameters of the modules can be different from those provided by the manufacturer; moreover, such parameters can change as the module is getting older. Therefore, the behavior of the mathematical model of a PV module can't match the real operating conditions. The paper proposes an improved model of a PV module that make use only parameters provided by manufacturers datasheets without requiring the use of any numerical methods. In the paper after the detailed description of the proposed model, different simulation results are pointed out. Finally a suitable procedure that permits to account the real operating parameters in the PV model and an experimental validation is presented.**

I. INTRODUCTION

Renewable energy generation systems, based on photovoltaic (PV) modules, nowadays represent the most suitable solution, in particular for domestic power levels, to reduce CO_2 emissions and the energy consumption produced by oil and gas. Moreover in different European countries, electricity companies are providing money incentives for the energy produced by renewable sources and injected into the utility grid. The cost and the performance of PV plants strongly depends on modules. However, the electrical parameters of the modules, i.e. open circuit voltage and short circuit current, can be different than those provided by the manufacturer; moreover, such parameters can change as the module is getting older. Therefore, the behavior of the mathematical model of a PV module can't match the real operating conditions.

Different model of solar cells were presented in literature [1-5]. The most accurate model, denoted as double-diode model [1], uses an equivalent circuit with two diodes but it is quite complex due to the presence of a double exponential and six parameters to assign. A different model, based on a single diode circuit, was then proposed in [2, 3]. In both cases, the mathematical models require the knowledge respectively of six and five parameters that are not directly available on manufactures datasheets. A simplified one-diode model, shown in Fig.1, using only four parameters was proposed in [4]. However, in such model the voltage is independent from solar irradiance. As consequence, a significant voltage error in the I-V curves is present specially at open circuit and maximum power point conditions. Finally a model with all parameters achievable from manufactures datasheet is proposed in [5]. The parameters determination of such model requires the use of numerical methods.

The paper proposes an improved model of a PV module that make use only parameters provided by manufacturers datasheets and, moreover, doesn't require any numerical methods. In the paper after the detailed description of the proposed model, different simulation results are pointed out. Finally an experimental validation of the model is presented together with a suitable procedure that takes into account the real operating parameters in the PV model.

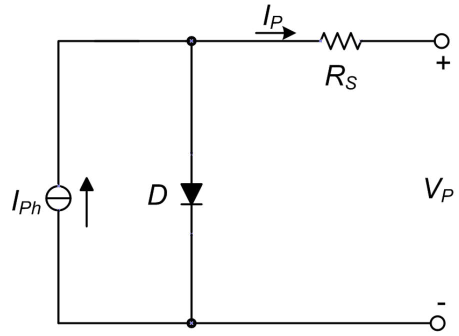

Fig. 1 – Single-diode equivalent circuit of a PV module.

II. MODEL OF A PHOTOVOLTAIC MODULE

The current of a PV module can be expressed, as function of voltage, by the simplified expression derived from [4]:

$$I_P = I_{SC} \cdot \left[1 - C_1 \cdot \left(e^{\left(\frac{V_P}{C_2 \cdot V_{OC}}\right)} - 1\right)\right] \quad (1)$$

where

$$C_1 = \left(1 - \frac{I_{MPP}}{I_{SC}}\right) \cdot e^{\left(\frac{-V_{MPP}}{C_2 \cdot V_{OC}}\right)} \quad (2)$$

$$C_2 = \frac{\left(\frac{V_{MPP}}{V_{OC}} - 1\right)}{\ln\left(1 - \frac{I_{MPP}}{I_{SC}}\right)} \quad (3)$$

Coefficients C_1 and C_2 depends on the following module parameters:

- short circuit current I_{SC};
- open circuit voltage V_{OC};
- maximum power point voltage V_{MPP};
- maximum power point current I_{MPP}.

Such parameters can be expressed as follow:

$$I_{SC}(G,T) = I_{SCS}\frac{G}{G_S}[1+\alpha(T-T_S)] \quad (4)$$

$$V_{OC}(T) = V_{OCS}+\beta(T-T_S) \quad (5)$$

$$I_{MPP}(G,T) = I_{MPPS}\frac{G}{G_S}[1+\alpha(T-T_S)] \quad (6)$$

$$V_{MPP}(T) = V_{MPPS}+\beta(T-T_S) \quad (7)$$

where parameters I_{SCS}, V_{OCS}, I_{mpps} and V_{mpps} are defined at standard conditions, STC (G_s=1000W/m^2 and T_s=25°C) and α and β are respectively the current and the voltage temperature coefficient; all the above parameters are provided by manufacturers on module datasheet. It is possible to note that the parameters referred to currents depends on module solar irradiance G and temperature T, while the voltage ones depends only on temperature.

To improve the accuracy of the model it is convenient to modify expressions (5) and (7) inserting a correction term, $\Delta V(G)$, taking into account voltage variation as function of solar irradiance:

$$V_{OC}(G,T) = V_{OCS}+\beta(T-T_S)-\Delta V(G) \quad (8)$$

$$V_{MPP}(G,T) = V_{MPPS}+\beta(T-T_S)-\Delta V(G) \quad (9)$$

Correction term $\Delta V(G)$ is obtained by the following relationship:

$$\Delta V(G) = V_{OCS}-V_{OCm}$$

where voltage V_{OCm} represents the open circuit voltage of the IV curve translated from STC to the considered irradiance G and it defined as:

$$V_{OCm} = C_2\cdot V_{OCS}\cdot \ln\left[1+\frac{\left(1-\frac{I_t}{I_{SCS}}\right)}{C_1}\right].$$

I_t is the short circuit current at irradiance G and can be written as:

$$I_t(G) = I_{SCS}\frac{G}{G_S}.$$

In order to determine the value of series R_S, as function of panel parameters, it is convenient to express the module voltage as function of current by inverting eq. (1):

$$V_P = C_2\cdot V_{OC}\cdot \ln\left[1+\frac{\left(1-\frac{I_P}{I_{SC}}\right)}{C_1}\right] \quad (10)$$

The value of series resistance R_S can be calculated by deriving eq. (10) with the current calculated for $I_P=0$:

$$-R_S = -\left.\frac{dV_P}{dI_P}\right|_{I_P=0} = \left(C_2\cdot\frac{V_{OC}}{I_{SC}}\right)\cdot\left(\frac{1}{1+C_1}\right) \quad (11)$$

III. SIMULATION RESULTS

The behavior of the proposed PV model has been simulated, in Matlab-Simulink environment, considering the parameters, at STC, of Photowatt PW1650 – 24V panel listed below:

- I_{SC} = 5.3 A;
- V_{OC} = 44.6 V;
- V_{MPP} = 35.4 V;
- I_{MPP} = 4.95 A;
- α = 1.46 mA/°C;
- β = –158 mV/°C.

In order to verify the model under different operating conditions, several tests have been performed at various temperature and solar irradiance values. Fig. 2 shows I-V curves for various solar irradiance (G varies from 100W/m^2 to 1000 W/m^2), while Fig. 3 illustrates I-V curves for different temperature values (T varies from -10°C to 65°C).

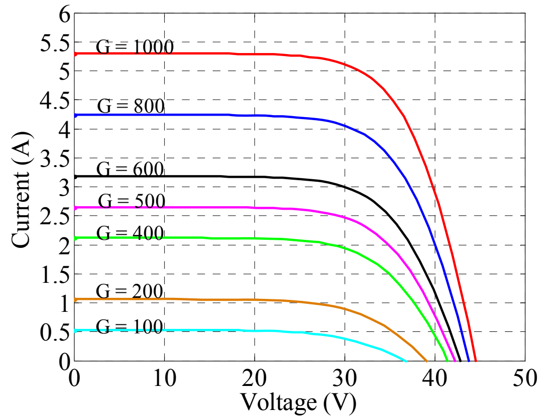

Fig. 2 – I-V curves obtained by simulation for various irradiation levels.

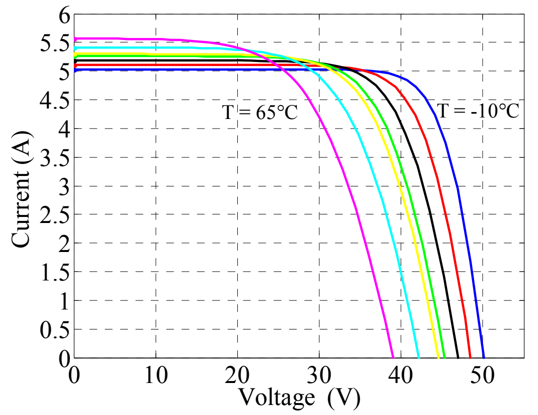

Fig. 3 - I-V curves obtained by simulation for various temperature values.

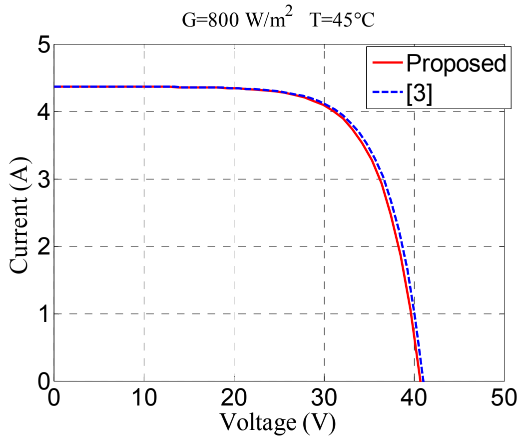

Fig. 4 – Comparison of I-V curves obtained by simulation.

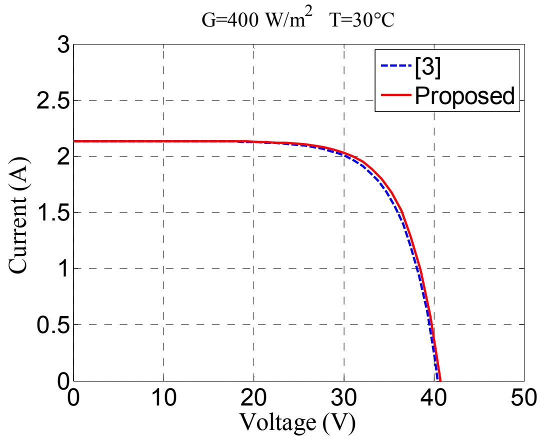

Fig. 5 - Comparison of I-V curves obtained by simulation.

In order to evaluate the performance of the proposed model a comparison with model presented in [4] was performed by different simulation tests.

Figs. 4 and 5 show the comparison of the IV curves obtained respectively for G = 800 W/m^2 T=45°C and G = 400 W/m^2 T=30°C. In the figures the continuous line represents the curve obtained with proposed model while, the dotted line, the curve achieved with the model described in [3]. It is possible to notice that, in both cases, the two curves present a similar shape without any significant discrepancy; therefore, in the successive comparisons the proposed model will be used.

IV. EXPERIMENTAL RESULTS

Several tests have been carried out on a Photowatt PW1650 – 24V polycrystalline photovoltaic module in the outdoor ESTER facility located on the roof top of the Engineering building of the University of Rome Tor Vergata [6]. The module has been exposed to the real environment since October 2007. It has been mounted on a south oriented frame with variable tilt angle. The module has been constantly monitored keeping it at maximum power point using an electronic device (MPPT3K) provided by ISAAC – SUPSI, Lugano, Switzerland. Every minute module maximum power, module temperature, in plane irradiance, air temperature and wind speed and velocity are collected and stored in a database. Every 10 minutes a complete IV curve is traced for each module under test. In plane irradiance is measured by an EKO pyranometer with an uncertainty of 3% at 1000 W/m^2 and by a polycrystalline reference cell (ISET sensor) with an uncertainty of 4% in the whole range. Module temperature is measured by a Pt100 attached on the back of the module. Temperature uncertainty has been estimated to be +/- 0.16°C.

IV curves collected with the described system as been compared with others measured using an acquisition system built in our laboratory, based on a switched capacitor [7] and shown in Fig. 6. Such approach permits to obtain similar performance on I-V curve tracking than traditional ones but simple implementation, lower costs and fast acquisition time.

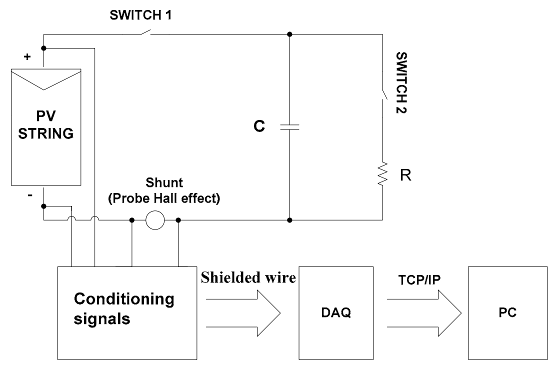

Fig. 6 – Acquisition system used for experimental tests.

A first test has been performed on the considered panel using both measurement systems to validate the prototype built in our laboratory. Since the experimental measures have been achieved at different temperature and solar irradiance, therefore it has been necessary to translate both curves to STC. The obtained results have been compared as shown in Fig. 7.

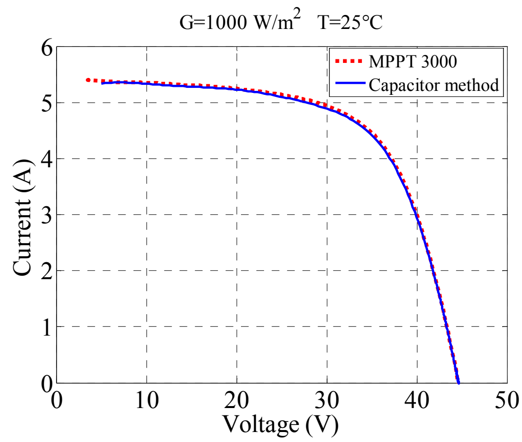

Fig. 7 – Comparison of I-V curves obtained by experimental test.

The translation has been performed according to [8] that describes the procedures for temperature and irradiance corrections to the I-V characteristics of a crystalline silicon PV module. Using this standard, each current-voltage pair (I_M, V_M) on the measured I-V curve is transformed into a corresponding pair at STC (I_{STC}, V_{STC}) by the following equations:

$$I_{STC} = I_M \cdot \left(\frac{G_{STC}}{G_M}\right)$$

$$V_{STC} = V_M + DV - R_s \cdot (I_M - I_{STC})$$

where:

$$DV = a \cdot \ln\left(\frac{G_{STC}}{G_M}\right) + b \cdot (T_M - T_{STC}).$$

The coefficients a and b are calculated by a least square procedure applied on the expression shown below:

$$V_{OC,STC} = V_{OC,M} + a \cdot \ln\left(\frac{G_{STC}}{G_M}\right) + b \cdot (T_M - T_{STC}).$$

It is possible to note, from Fig. 7, that the I-V curves don't present significant discrepancy; therefore, the acquisition system of Fig. 6 is used to perform the following tests.

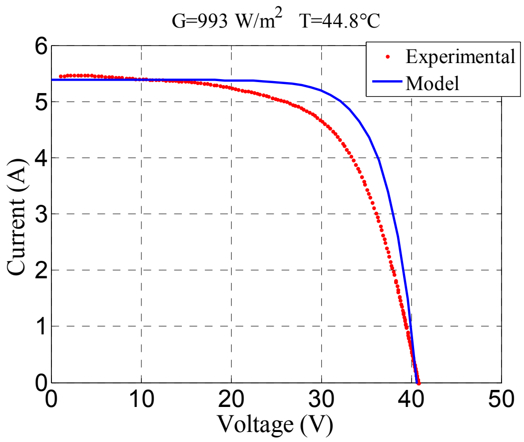

Fig. 8 – Comparison of I-V curves obtained by simulation and experimental test.

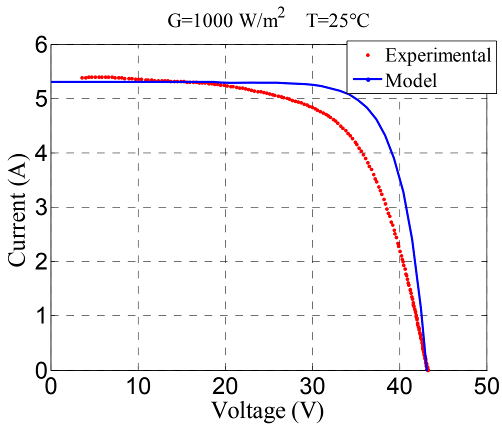

Fig. 9 – Comparison of I-V curves obtained by simulation and experimental test at STC.

Fig. 8 shows the comparison among the simulation result obtained with the proposed model (continuous line) and the experimental curve (dotted line) measured at G = 993 W/m^2 and T=44.8°C. Fig. 9 illustrates the IV curves, referred to the same test, translated to STC.

The difference between the simulation model and the experimental curve is due to the different parameters values of the tested panel respect to the theoretical ones furnished on the datasheet.

In order to consider those variations, authors propose to modify the PV model introducing two additional resistors, R_{SX} and R_{PX}, as shown in Fig. 10.

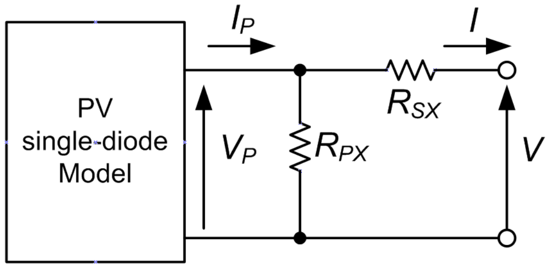

Fig. 10 – Modified model of PV module.

Resistors R_{SX} and R_{PX} can be identified using the following procedure.

The value of parallel resistance R_{PX} can be determined by:

$$R_{PX} = \left.\frac{\Delta V_E}{\Delta I_E}\right|_{I_{SC}}$$

where ΔV_E and ΔI_E are taken from the experimental data nearby the short circuit current.

The value of series resistance R_{SX} can be determined as:

$$R_{SX} = \left.\frac{\Delta V_E}{\Delta I_E}\right|_{V_{OC}} - R_S$$

where ΔV_E and ΔI_E are taken from the experimental data nearby the open circuit voltage and R_S is calculated using (11).

Finally, the output current I of the new model can be expressed as:

$$I = I_P - \frac{V_P}{R_{PX}}$$

and the output voltage V of the new model is:

$$V = V_P - R_{SX} \cdot I$$

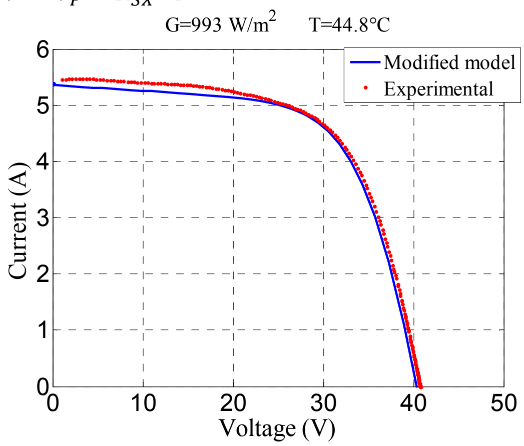

Fig. 11 – Comparison of I-V curves obtained by simulation and experimental test.

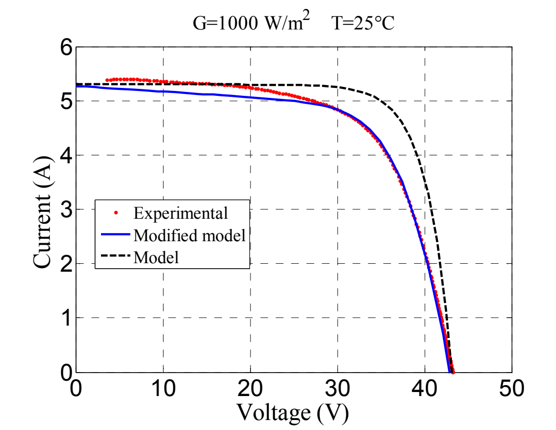

Fig. 12 – Comparison of I-V curves obtained by simulation and experimental test at STC.

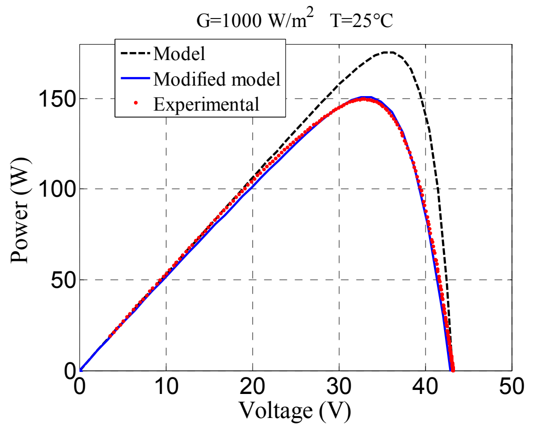

Fig. 13 – Comparison of I-V curves obtained by simulation and experimental test at STC.

To verify the proposed procedure a comparison among the experimental curve, obtained in the same operating condition of Fig. 8, the curves achieved by simulation with the model described in section II and the modified model has been performed. The results of the comparison of the IV curves are shown in Figs. 11 and 12 respectively for real operating conditions and STC, while in Fig. 13 is represented the comparison among the power waveforms at STC.

As it possible to notice from the figures above, the experimental curve (dotted line) and the modified model curve (continuous line) are very similar, while the curve of the initial model (dashed line) presents significant differences from the others. Fig. 13 highlights that the maximum peak power of the module provided by the manufacturer datasheet is not correspondent to the experimental one.

V. CONCLUSION

The paper presents an improved mathematical model for photovoltaic modules that employs only parameters provided by manufacturers datasheets without requiring the use of any numerical methods. The model is derived from [4] by applying several improvements, such as an opportune correction term that permit to account the voltage variation as function of the solar irradiance.

However, the electrical parameters of the modules, i.e. open circuit voltage and short circuit current, can be different than those provided by the manufacturer; moreover, such parameters can change as the module is getting older. Therefore, the behavior of the mathematical model of a PV module can't match the real operating conditions. In such framework, authors propose a suitable modification to the model to take into consideration the real operating parameters in the PV model.

Several simulation and an experimental results have been pointed out in order to validate the mathematical model. The results show that the proposed model demonstrates a good agreement with the experimental data measured by an acquisition system specific for I-V characteristics measurements.

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