Virtual Sensing of Photovoltaic Module Operating Parameters

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Abstract—The single diode equivalent circuit allows describing photovoltaic panels behavior quite accurately. The values of the five parameters appearing in this model are usually identified in Standard Test Conditions, at which irradiance and temperature values are given. Instead, when this identification has to be performed on field, suitable environmental sensors are required. In this paper, a method is presented for identifying the single diode model parameters as well as the irradiance and temperature conditions at which the panel is actually working. The method has the measured panel current vs voltage curve as the only input and it is suitable for being implemented on an embedded system for field applications. The method is validated through a large database of experimental results.

Index Terms—Photovoltaic systems, parameters identification, condition monitoring, diagnosis.

I. INTRODUCTION

Photovoltaic (PV) panels are usually modeled through the Single Diode Model (SDM) shown in Fig. 1 [1]. It is a good trade-off between complexity and accuracy including a current generator, the DC current thereof mainly depending on the irradiance at which the panel works, a diode, which models the PN junction, and two resistors reproducing the power loss mechanisms.

The parameters appearing in this model are the photo induced current $I_{ph}$, the saturation current $I_s$, and the ideality factor $\eta$ of the diode and the shunt and the series resistances $R_{sh}$ and $R_s$, respectively. By this model, the PV current $I$ is calculated for every positive value of PV voltage $V$, by solving a nonlinear equation or by using the following explicit expression, which employs the Lambert W-function [1].

$$I = \frac{R_{sh} (I_{ph} + I_s) - V}{R_s + R_{sh}} - \frac{a}{R_s} W(\theta)$$  \hspace{1cm} (1)

with:

$$\theta = \frac{R_s R_{sh} I_s}{a (R_s + R_{sh})} e^{\frac{R_s R_{sh} (I_{ph} + I_s) + R_{sh} V}{a (R_s + R_{sh})}}$$  \hspace{1cm} (2)

and:

$$a = \frac{N_s \eta k T}{q}$$ \hspace{1cm} (3)

In (3), $N_s$ is the number of series-connected cells in the panel, $k$ is the Boltzmann constant and $q$ is the electron charge. In addition to the explicit dependency on the cell temperature $T$ shown in (3), the photo induced and saturation currents have major dependencies on the irradiance level $G$ and on the cell temperature $T$ that have to be taken into account. Indeed, the photo induced current shows the following relationship [1]:

$$I_{ph} = I_{ph, STC} \frac{G}{G_{STC}} \left[1 + \alpha_l (T - T_{STC})\right]$$ \hspace{1cm} (4)

where $\alpha_l$ is the thermal coefficient of the panel short circuit current and all the quantities having the subscript STC are referred to the Standard Test Conditions (STC), that are $G_{STC}=1 \text{ kW/m}^2$ and $T_{STC}=25 \degree C$. Values of parameters in STC are typically given by the manufacturer in the panel data sheet. The cell temperature also significantly affects the PV cell saturation current, according to the following equation:
\[ I_s = C_{STC} T^3 e^{\frac{E_g(T)}{kT}} \]  

(5)

where \( C_{STC} \) is a coefficient that is calculated at STC [1] and \( E_g(T) \) is the material band gap at the temperature \( T \), which is determined as [2]:

\[ E_g(T) = E_{g,STC} \left[ 1 + \alpha_e \cdot (T - T_{STC}) \right] \]  

(6)

wherein the thermal coefficient of the energy gap is assumed to be equal to \( \alpha_e = 0.000277 \) K\(^{-1}\). The analytical model given by (1)-(6) is commonly used for simulating the PV module at any condition \( \{G, T\} \), provided that the values of the five parameters:

\[ P_{STC} = \{I_{ph,STC}, I_{s,STC}, \eta_{STC}, R_s, R_{sh,STC}\} \]  

(7)

have been identified in STC. This goal can be achieved in different ways and the current literature proposes many possible approaches. Some of them use optimization algorithms for minimizing the root mean square error between the STC current vs voltage \((I-V)\) curve provided by the manufacturer and the curve obtained by the identified set of parameters [1]. An effective application of the optimization algorithms often requires the careful analysis of the search space [3]. Other approaches, e.g. [4][5], symbolically manipulate a set of five non-linear equations in order to have a reduced set that is, again, solved by a minimization algorithm. Moreover, some papers propose the use of an approximated set of five explicit equations allowing to calculate the five parameters explicitly, thus without using iterative numerical procedures [1][6].

Unfortunately, only few papers, e.g. [5][7], are dedicated to the identification of the five parameters \( \{I_{ph, I_s, \eta, R_s, R_{sh}}\} \) in operating conditions that are not the STC, wherein the \( \{G,T\} \) values are assigned. Some methods, which are almost the same used in STC, use as an additional information the actual \( \{G,T\} \) values obtained through suitable irradiance and temperature sensors, the latter measuring the ambient temperature or the temperature at the panel backside. Literature formulas for predicting the cell temperature \( T \) from those measurements are also used [1][8].

The numerical approach proposed in this paper does not identify the five SDM parameters of a PV panel. Instead, by exploiting the well known dependency that some of them have on the operating irradiance and temperature, the proposed algorithm is aimed at identifying the working conditions, thus \( \{G,T\} \), and the values of a reduced set of the SDM parameters of the PV panel during outdoor operation. The method starts from the full identified set of parameters \( \{I_{ph,STC}, I_{s,STC}, \eta_{STC}, R_s, R_{sh,STC}\} \) in STC determined through explicit formulas and then exploits equations (1)-(6) for the identification procedure in real operating conditions. Because of its low computational burden, it has a high potential of being implemented in a low cost embedded processor for on-site applications, e.g. incorporated into a micro inverter or a power optimizer. Identification of the actual values of parameters such as \( R_s \) and \( R_{sh} \) provides information about the current state of health of the PV panel. Thus, the proposed approach can be further extended to develop PV module monitoring and diagnostic algorithms.

The manuscript is organized as follows. Section II describes the numerical approach. Section III shows how the algorithm performs in different conditions by using a huge number of experimental data. Section IV is dedicated to conclusions and possible applications of the algorithm.

II. THE IDENTIFICATION ALGORITHM

The algorithm assumes that the type and model of PV panel is known, so that the STC data can be taken from the data sheet provided by the manufacturer. This allows determining the values of the five SDM parameters in STC by using the method presented in [1][6]. It has been shown in literature that this approach guarantees accurate parameters identification in STC with a low computational effort.

The achieved set of parameters in STC is used as a guess solution for the following numeric procedure. The \( I-V \) curve of the PV panel working in outdoor conditions is assumed to be the input to the proposed algorithm. No additional information about the PV panel operating conditions, especially the \( G \) and \( T \) values, is assumed to be known. According to (3), (4), (5) and (6), these ones non linearly affect the model (1) used for the \( I-V \) curve identification.

According to the literature [2], the diode ideality factor has been kept fixed at its STC value \( \eta = \eta_{STC} \). Thus, the identification problem has been scaled down to four parameters \( \{I_{ph}, I_s, R_s, R_{sh}\} \). Moreover, it has been noted that formulas (4)-(6) give the relationship between \( \{I_{ph}, I_s\} \) and \( \{G, T\} \), so that the four parameters to identify can be turned into:

\[ P = \{G, T, R_s, R_{sh}\} \]  

(8)

Thus, a fitting procedure is set up to identify the values of these four parameters: it is based on the minimization the Root Mean Square Error (RMSE) between the \( I-V \) curve given by the SDM (1) and the experimental one. The identification process has been performed by using a classical Trust Region non-linear minimization approach, with a termination condition fixed on both the RMSE value and the identified parameter values. Both termination tolerances have been fixed at \( 10^{-10} \). Guess solution to start the minimization method is based on (7), thus it is \( \{G_{STC}, T_{STC}, R_s, R_{sh,STC}\} \).

Fig. 2 shows the flowchart of the proposed procedure for a single \( I-V \) curve. It can be applied as well to a sequence of \( I-V \) curves acquired time by time on the same PV panel. In the latter case, especially if the time interval between two consecutive acquisitions is not too large, the guess solution for the fitting algorithm can be the algorithm output set (8) achieved for the previous \( I-V \) curve. Such a loop has been used for obtaining the results shown in the following Section.
III. EXPERIMENTAL RESULTS

The experimental data acquired on the PV panels available at the Tampere University of Technology [9] have been used to validate the proposed procedure. The first test has been done on measurement data referring to a single NAPS NP190GKg PV panel, which includes 54 poly-crystalline silicon cells. Its electrical performance in STC as reported in the data sheet is summarized in Table I.

| Parameter  | Value       |
|------------|-------------|
| $I_{sc}$   | 8.00 A      |
| $I_{MPP}$  | 7.36 A      |
| $V_{oc}$   | 33.0 V      |
| $V_{MPP}$  | 25.8 V      |
| $\alpha_I$ | 0.0047 A/K  |
| $\alpha_V$ | -0.124 V/K |

Table I. Electrical parameters of the NAPS NP190GKg panel in STC.

First of all, the five parameters of the single diode model in STC have been identified through the explicit formulas proposed in [1][6]. The achieved set of parameters is shown in Table II.

| Parameter            | Guess solution   |
|----------------------|------------------|
| $I_{ph,STC}$         | 8.00 A           |
| $I_{STC}$            | 1.6993 nA        |
| $\eta_{STC}$         | 1.0686           |
| $R_{s,STC}$          | 0.3786 $\Omega$  |
| $R_{sh,STC}$         | 122.56 $\Omega$  |

Table II. SDM parameters for the NAPS NP190GKg panel in STC.

Some of these parameter values have been used to define the search space and to provide the guess solution of parameters for the Trust Region minimization algorithm used for the identification. Table III collects these values, which refer to the irradiance and temperature and to the series and shunt resistances. It is worth noting that the guess solution is based on data referring to STC conditions taken from Table II and the ranges are determined quite easily on the basis of the typical working conditions of the cells, thus G and T in the installation site, and of typical values of the two resistances appearing in the SDM.

| Parameter  | Guess solution | Range       |
|------------|----------------|-------------|
| $G$ [W/m$^2$] | 1000           | [10,1300]   |
| $T$ [°C]   | 25             | [0,70]      |
| $R_s$ [$\Omega$] | 0.3786       | [0.1,5]     |
| $R_{sh}$ [$\Omega$] | 122.56     | [50,500]    |

Table III. Guess solution and search space of the four parameters to identify.

III.A First example

The first identification test has been done by processing four hours of operation of the PV panel. One I-V curve per second is measured. Thus the parameters $\{G, T, R_s, R_{sh}\}$ have been identified, in sequence, for the 14400 I-V curves of the set. Each curve has been acquired by sampling the voltage range $[0, V_{oc}]$ in 4000 equally spaced points.

For the first curve, the guess solution has been the one shown in Table III. Because each curve has been acquired 1 s after the previous one, from the second curve on the guess solution has been settled as the identified set of parameters $\{G, T, R_s, R_{sh}\}$ of the previous curve. It is worth noting that the validation of the method has not been done on single curve, because only a partial validation of the performance of the method would have been achieved. An analysis on a long sequence of curves and different operating conditions is useful also for having an idea of the potential use of the proposed approach in real PV control, monitoring and diagnostic applications.

Fig.3 shows the comparison between the irradiance level $G$ identified by the procedure and the one measured by a pyranometer [9]. The overestimation of the measured irradiance has been assessed to be due to a value of the short circuit current in STC declared by the PV panel manufacturer that is smaller than the real one. Indeed, some experimental tests done on the panel by measuring the ratio $I_{oc}/G$ in different conditions reveal that measured short circuit current is higher than the one declared by the manufacturer in the data sheet in STC. Comparison of the experimental measurement and the identified values in Fig. 4 confirms the slight overestimation.

Fig.5 and Fig.6 show the comparison between the measured and the estimated temperatures. It is worth remarking that the measured values are acquired through a PT100 sensor placed on the backside surface of the PV panel [9]. Instead, the estimated temperature is the cell’s one, as it is evident from the equations (3)-(6) used in the model. The temperature difference between the PV cell and the backside of the PV panel increases linearly with the increase of the irradiance received by the panel. Thus the cell temperature can be estimated to be 1 °C higher than the panel backside temperature at 1 kW/m$^2$ irradiance by using the PV panel material heat conductivities documented in literature [10]. Consequently, the identification of the cell temperature achieved through the proposed approach is reasonably accurate. The accuracy, of both $G$ and $T$, has to be considered in relation with the simple model used as virtual sensor.
As stated in the previous Section, for each I-V curve, also the values of series and shunt resistances have been identified. The results for the full sequence of 14400 I-V curves are shown in Fig. 7 and in Fig. 8 for $R_s$ and $R_{sh}$, respectively. $R_{sh}$ keeps always at high values, in some cases reaching the upper bound fixed in Table III. The minimization method used for the parametric identification explores the upper part of the $R_{sh}$ range without improving the accuracy significantly. This happens especially at low irradiance levels, where $R_s$ reaches a higher value. Both these behaviors are also documented by [2][11]. The identified value of the series resistance at high irradiance can be compared with the STC one in Table II considering that the measurements on the PV panel are not performed exactly at the panel’s terminals. Indeed, two cables of 53.5 m length and having a total equivalent resistance of 0.363 Ω are used for acquiring the I-V curves in the TUT laboratory.
III.B Second example
A second set of $I$-$V$ curves has been considered, again referring to four hours of PV panel operation in real conditions. Low irradiance and low temperature conditions have been considered in this case, in order to highlight the limit of the proposed approach in such conditions. Fig.9 and Fig.10 show the measured and identified $G$ and $T$. As for the first example, the temperature is measured at the backside of the PV panel; instead, the cells temperature has been identified through the method presented in this paper. Fig.9 and Fig.10 put into evidence that, although the model catches the variations and the overall behavior, the estimation error increases clearly with decreasing irradiance. The reason of this is in the well-known limitations of the SDM and of the equations adopted when the operating conditions move far from the STC. These limitations of the used model are visible, in particular, in the identified PV cell temperature in Fig. 10 when irradiance fluctuates between high and very low values. The estimated series and shunt resistances are shown in Fig.11 and Fig.12, respectively. Their magnitudes are in line with those ones obtained in the previous test case, but their variation is much higher. Since this second example considers mainly low irradiance conditions, the identified shunt resistance keeps almost always very high, often reaching the upper bound of the search space. This behavior is consistent with the results shown in the previous Section.
III.C Third example

A further test has been done starting from the same set of $I$-$V$ curves used in the first example but, for each curve, only a reduced number of samples around the Maximum Power Point (MPP) has been considered. Indeed, in real applications, the PV panel energy production might be too much penalized by the scan of the whole $I$-$V$ curve, also at low current and voltage values, hence towards $V_{oc}$ and $I_{sc}$. Thus, only the points in the range $[V_{MPP} - 3 \text{V}, V_{MPP} + 3 \text{V}]$ have been considered for each $I$-$V$ curve. This range corresponds to almost one fifth of the range $[0, V_{oc}]$ and the power production is not too much penalized as the PV panel is working around its MPP during normal operation, e.g. driven by a Perturb and Observe MPP Tracking method.

In Fig.13 an example of $I$-$V$ curve identification is shown. The black points around the MPP are the only ones used for the parametric identification based on the algorithm proposed in this paper. As expected, the identification of the constant-current part of the curve, including $I_{sc}$, is less accurate than the constant-voltage one, including $V_{oc}$. This is evident by looking at the red curve, which is the one reconstructed by using the parameters identified by means of the black samples only. The choice of a symmetric interval around the voltage value where the MPP occurs is the main reason of such inaccuracy. The higher slope of the curve at the right side of the MPP covers a larger portion of the curve thereof, leading to a better curve fitting at high voltages.

By comparing the red curve of the identified irradiance in Fig.14 with the corresponding one in Fig.3, it is evident that the intelligibility of the reconstructed $G$ is not seriously compromised. The curve is at first hand just more noisy because of the less accurate identification of the short circuit current, as it has been demonstrated in Fig.13. The identified temperature is also affected by identification noise accordingly, as can be noticed by comparing Fig.15 with Fig.5. The $R_s$ identification is an apparent sequel of these results, as it can be seen in Fig.16. The two $R_s$ identifications are compared in Fig.17. In black color, the series resistance identified using all the samples of the curve as in the first example discussed in Section III.A (see Fig.7) is shown. In red color, the series resistance identified as proposed in this Section is depicted. The comparison has been limited to a time interval corresponding to high irradiance level. The noisy curve based on the reduced samples gives a slight overestimation, on the average, with respect to the more accurate parameter identification based on the full $I$-$V$ curve. As expected, the reduced number of samples used for the identification reduces the accuracy and increases the variation of identified $R_s$ values recognized through the proposed method.

III.D Fourth example

The last example refers to a series connected string of 17 PV panels of the same type used in the previous examples. The irradiance sensor is attached to the same panel where the temperature sensor is installed. In this example, the panels may not operate under uniform $G$ and $T$ conditions, which may cause larger differences between identified and measured values. Fig.18 and Fig.19 show also in this case a reasonable accuracy of the identified irradiance and temperature, respectively. One must again take into account the inaccuracy
of the data sheets values and the difference between the PV panel backside temperature and the cells temperature. The latter discrepancy is also accentuated by the uneven distribution of the temperature among the cells of the 17 panels in series. The series resistance identification shown in Fig.20 indicates an average value that is compatible with the one obtained for the single panel at high irradiance (see Fig.7). It is worth noting that some anomalous identified $R_s$ values are due to a temporary mismatch affecting the string. This is clearly shown in Fig.21 where three $I-V$ curves are plotted: in black color, the two $I-V$ curves acquired one second before and one second after the event corresponding to the highest observed $R_s$ value (just after 9:30). In red color instead, the mismatched curve acquired in that instant and giving rise to the incorrect identification. This is evidently due to the fact that the considered model is not able to operate on $I-V$ curves corresponding to mismatched conditions. The identified shunt resistance values are shown in Fig.22. The effect of anomalous identification is also evident in few cases.

![Fig. 15. Measured PV panel backside (black) and identified cell (red) temperatures in the third example.](image)

![Fig. 16. Identified values of the series resistance in the third example.](image)

![Fig. 17. Identified series resistances in the case of identification through the whole $I-V$ curve (black) and through the samples in the range $V_{MPP} \pm 3V$ (red).](image)

![Fig. 18. Identified (red) and measured (black) irradiance for the string of 17 panels in the fourth example.](image)

![Fig. 19. Identified cell temperature (red) and temperature at the backside of one of the 17 panels in the string (black) in the fourth example.](image)
In this paper a numerical method for the identification of the operating conditions of a PV generator is presented. The approach is based on the $I$-$V$ curve acquired in the actual operating conditions and on data that are commonly made available by the manufacturer through the PV panel data sheet. The approach is based on well-assessed formulas referring to the single diode model of the cells and panels. The approach has been tested on several cases by using outdoor experimental measurements. The accuracy and limitations of the virtual sensor, especially at low irradiance levels, have been documented and they were not unexpected. Some discrepancies might be reduced by using an improved model in terms of dependencies of the SDM parameters from $G$ and $T$. Given the relationship between the estimated parameters and the state of health of the PV panels, the proposed approach can be further extended for developing monitoring and diagnostic algorithms, also in consideration of its possible implementation on an embedded system for on-field operation even as a tool integrated into panel-dedicated electronics.

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![Fig. 20. Identified series resistance of the string of 17 panels in the fourth example.](image1)

![Fig. 21. Measured $I$-$V$ curve corresponding to the inaccurate parameter identification in the case of partial shading conditions (red), and $I$-$V$ curves measured one second before and one second after under uniform conditions (black, superimposed).](image2)

![Fig. 22. Identified shunt resistance of the string of 17 panels in the fourth example.](image3)