European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality (ICREPQ'10)
Granada (Spain), 23th to 25th March, 2010

Identification of Photovoltaic Array Model Parameters. Modelling and Experimental Verification

I. Houssamo[1], M. Sechilariu[1], F. Locment[1] and G. Friedrich[2]

University of Technology of Compiegne
[1]AVENUES Team Research
BP 60319 - 60203 Compiegne (France)
Phone/Fax number: +33 344234964/+33 344235262
e-mail: **issam.houssamo@utc.fr**, **manuela.sechilariu@utc.fr, fabrice.locment@utc.fr**

[2]LEC, EA 1006
BP 20529 – 60205 Compiegne Cedex (France)
Phone/Fax number: +33 344234515/+33 344237937
e-mail: **guy.friedrich@utc.fr**

Abstract. This paper aims to identify the model parameters of a photovoltaic array installed in our experimental platform. Two methods used for parameters identification in order to characterize the photovoltaic array are compared. Based on the electrical equivalent circuit of the photovoltaic cell, the mathematical model is deduced. From the data-sheet values, given by the manufacturer, we were able to determine the parameters of this model. On the other hand, the second method was applied by using one of the least squares fitting approaches. The measurement of the outdoor solar irradiance, cell temperature and current taken by dSPACE controller board and for a constant terminal voltage level includes the necessary data to be fitted with the model. The implementation of two methods in MATLAB provides the model parameters which have to minimize as soon as possible the error involved between the calculated and measured output current. For the minimum obtained error, the corresponding method is the best one for the photovoltaic array characterization.

Key words

Photovoltaic, Modelling, Least squares fitting, Simulation.

1. Introduction

For self-feeding building with renewable electricity, the semi-isolated and safety network is proposed to overcome the technical constraints related to connecting distributed sources with the utility grid. For this purpose we are interested to modelling a photovoltaic array (PVA). The knowledge of the model parameters is essential to evaluate the PVA behaviour under all operating conditions. However, the manufacturers give just the electrical features of photovoltaic (PV) panel under the standard test conditions (STC). Thus, many works focused on the identification of the unknown parameters of the PV or PVA model. As for many published literatures, a model based on the electrical equivalent circuit of the cell is proposed in this paper. In [1], a two-parameter PV model was characterised by adjusting the current-voltage (*I-V*) characteristic curve at the three points given by the manufacturer: open circuit, maximum power point and short-circuit. According to the cell equivalent circuit, an analytical four and five-parameter PV panel models were deduced and experimentally verified [2]. A simplified graphical method was used in [3]. Other publications use the robust linear regression methods [4] or the artificial neural network [5].

In this paper, two methods of PVA parameters identification are analyzed and compared in order to choose the most appropriate one to use in modelling of PVA installed in our experimental platform. Based on a single-diode PV cell circuit, a mathematical model is deduced. At the three operating points mentioned above, the first method is applied and allows finding its parameters. Concerning the other one, the error occurred between the calculated and measured output PVA current was minimized by using one of the least squares fitting approaches. Both methods are programmed in MATLAB. First, the PVA is described. Then, the mathematical model is presented. Subsequently, the measurement bench is given. After that, each algorithm is explained. Finally, for both cases, the output PVA currents are compared with the measured ones in order to find the best PVA parameter identification method.

2. PVA description

The experimental platform, shown in Fig. 1, has two PVA installed on the roof of centre Pierre Guillaumat 2 at the University of Technology of Compiegne in France.

Fig. 1. Experimental platform

The PVA consists of 8 PV panels Solar-Fabrik SF-130/2-125 electrically coupled on four parallel branches formed by two series PV panels (Fig. 2).

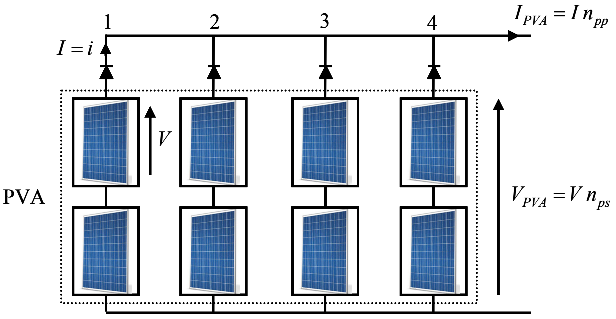

Fig. 2. Photovoltaic array

In order to protect the PV panels from the reverse current, one diode is placed in the head of each branch. Several poly-crystalline silicon cells are interconnected in series and packaged in each PV panel.

3. PVA modelling

Many models of varying complexity describing the behaviour of a PV cell are available. So, the number of parameters that need to be identified is different. In this paper, a single-diode PV cell model is proposed. It is the most classical model available in the literature [1]-[5]-[6]-[7]-[8] and has the electrical scheme shown in Fig. 3. It consists of a current generator for modelling the incident solar irradiance, a diode for the polarization phenomena, a series resistance and a parallel resistance for representing the power losses.

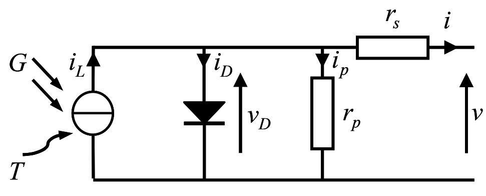

Fig. 3. Three-parameter PV cell electrical equivalent model

Using Kirchhoff's first law, the terminal current of the cell is:

$$i = i_L - i_D - \frac{v + i r_s}{r_p} \tag{1}$$

where i_L, given in (2), is the light-generated current. It is directly proportional of the incident solar irradiance (G), linearly related to cell temperature (T), and depends on the materials used and fabrication processes. The diode current is noted i_D. It is function of T, as given in (3). The dark saturation current, i_{sat}, is expressed in (4).

$$i_L = I_{sc}^{*}\left(\frac{G}{G^{*}}\right)\left(1 + K_i\left(T - T^{*}\right)\right) \tag{2}$$

$$i_D = i_{sat}\left(\exp\left(\frac{v + i r_s}{n V_T}\right) - 1\right) \tag{3}$$

$$i_{sat} = \frac{I_{sc}^{*}\left(\frac{T}{T^{*}}\right)^{\left(\frac{3}{n}\right)}\exp\left(\frac{-qE_g}{nk}\left(\frac{1}{T} - \frac{1}{T^{*}}\right)\right)}{\left(\exp\left(\frac{qV_{oc}^{*}}{nkT^{*}}\right) - 1\right)} \tag{4}$$

The STC are assumed to be the reference solar irradiance G^{*}=1000W/m^2 and the reference cell temperature T^{*}=298K at air masse equal to 1.5. Under these conditions, the manufacturer specifies some electrical features of the PV panel: short circuit current I_{sc}^{*}, open circuit voltage V_{oc}^{*}, temperature coefficient for current K_i expressed in mA/K, maximum output current I_{mpp} and maximum output voltage V_{mpp}. The quantities k, q are Boltzmann's constant and the electron charge. The thermal voltage is $V_T = kT/q$. E_g, is the band gap energy of semiconductor (it equals to 1.12eV for the silicon). The unknown parameter, n, is the diode ideality factor which takes a value between 1 and 2. Other unknown parameters are the series resistance, r_s, and the parallel resistance, r_p. The series resistance represents the semiconductor material resistance and those for contact interfaces. The parallel resistance represents the leakage current across the p-n junction.

Let n_s be the number of cells in series in one PV panel. The output panel voltage is $V = v\,n_s$, and the characteristic (I-V) of PV panel is given by (5).

$$I = i_L - i_{sat}\left(\exp\left(\frac{V + IR_s}{n n_s V_T}\right) - 1\right) - \frac{V + IR_s}{R_p} \tag{5}$$

where $R_s = n_s\,r_s$ and $R_p = n_s\,r_p$ are the panel series and parallel resistances. Considering that the numbers of the PV panel in series and respectively the parallel branches in the PVA are known as n_{ps} and respectively as n_{pp}, the general characteristic (I_{PVA}-V_{PVA}) of the PVA is:

$$I_{PVA} = n_{pp}\left[i_L - i_{sat}\left(\exp\left(\frac{V_{PVA} n_{pp} + I_{PVA} R_{ser}}{nNV_T}\right) - 1\right)\right] - n_{pp}\frac{V_{PVA} n_{pp} + I_{PVA} R_{ser}}{R_{par}} \tag{6}$$

The PVA series and parallel resistances are $R_{ser} = n_s\,n_{ps}\,r_s$ and $R_{par} = N\,r_p$, where $N = n_s\,n_{ps}\,n_{pp}$.

So, the (I_{PVA}-V_{PVA}) characteristic represents an implicit and non linear equation with two variables, G and T, and three unknown parameters: n and R_{ser} and R_{par}. This function can be expressed as follows:

$$I_{PVA} = f(G, T, I_{PVA}, V_{PVA}, P) \quad (7)$$

where P is the unknown parameters vector:

$$P = [n, R_{ser}, R_{par}] \quad (8)$$

4. Test bench

The parameters identification can be carried out by means of least squares fitting and by using the experimental measurements recorded at our test bench shown in Fig. 4. These measurements are I_m, V_m, G_m and T_m.

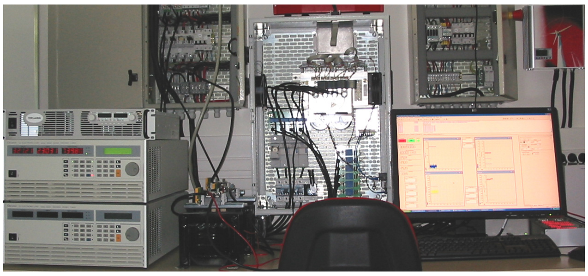

Fig. 4. Test Bench

All the experimental measurements are controlled in real time by dSPACE controller board. The measurements relating to the irradiance G_m and cell temperature T_m are carried out by a pyranometer and respectively by a PT100 sensor. The electrical equivalent circuit test is shown in Fig. 5.

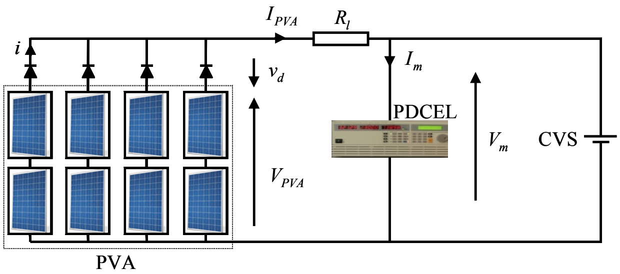

Fig.5. Measurement circuit

Using a controlled voltage source (CVS) and a programmable DC electronic load (PDCEL), for a constant voltage level (V_m), these measurements are made. In this test the CVS is just used for setting the load voltage at a constant level and it doesn't supply any current. All the PVA power is absorbed and dispersed by the PDCEL, thus $I_{PVA} = I_m$. The fact that the PVA is installed on the roof compels us to measure the voltage after the protection diode and the connecting cable. So, the voltage drop across the diode (v_d) and the connecting cable resistance (R_l), are accounted for as follows:

$$V_{PVA} = V_m + I_m R_l + v_d \quad (9)$$

5. Identification process

A. Determination of the PV panel model parameters from data-sheet values

For this first method, the values of the model parameters are calculated by using the specifications described in data-sheet. Accordingly, the operation conditions are the STC. So, the thermal voltage becomes:

$$V_T^* = \frac{kT^*}{q} \quad (10)$$

Writing the equation (5) for short-circuit point, maximum power point and open circuit point gives these three equations:

$$I_{sc}^* = i_L - i_{sat}\left(\exp\left(\frac{I_{sc}^* R_s}{n n_s V_T^*}\right) - 1\right) - \frac{I_{sc}^* R_s}{R_p} \quad (11)$$

$$I_{mmp} = i_L - i_{sat}\left(\exp\left(\frac{V_{mmp} + I_{mmp} R_s}{n n_s V_T^*}\right) - 1\right) - \frac{V_{mmp} + I_{mmp} R_s}{R_p} \quad (12)$$

$$0 = i_L - i_{sat}\left(\exp\left(\frac{V_{oc}^*}{n n_s V_T^*}\right) - 1\right) - \frac{V_{oc}^*}{R_p} \quad (13)$$

From (13) the current i_L and the current i_{sat} can be expressed:

$$i_L = i_{sat}\left(\exp\left(\frac{V_{oc}^*}{n n_s V_T^*}\right) - 1\right) + \frac{V_{oc}^*}{R_p} \quad (14)$$

By insertion (14) into (11), we obtain this equation:

$$I_{sc}^* = i_{sat}\left(\exp\left(\frac{V_{oc}^*}{n n_s V_T^*}\right) - \exp\left(\frac{I_{sc}^* R_s}{n n_s V_T^*}\right)\right) + \frac{V_{oc}^* - I_{sc}^* R_s}{R_p} \quad (15)$$

From the above equation, the current i_{sat} results in:

$$i_{sat} = \frac{I_{sc}^*\left(R_s + R_p\right) - V_{oc}^*}{R_p\left(\exp\left(\frac{V_{oc}^*}{n n_s V_T^*}\right) - \exp\left(\frac{I_{sc}^* R_s}{n n_s V_T^*}\right)\right)} \quad (16)$$

Insertion (14) and (16) into (12), the maximum output current will take the form:

$$I_{mmp}=\frac{\left(\exp\left(\frac{V_{oc}^{*}}{nn_sV_T^{*}}\right)-\exp\left(\frac{V_{mmp}+I_{mmp}R_s}{nn_sV_T^{*}}\right)\right)}{R_p\left(\exp\left(\frac{V_{oc}^{*}}{nn_sV_T^{*}}\right)-\exp\left(\frac{I_{sc}^{*}R_s}{nn_sV_T^{*}}\right)\right)} \tag{17}$$

$$\times\left(I_{sc}^{*}\left(R_s+R_p\right)-V_{oc}^{*}\right)+\frac{V_{oc}^{*}-V_{mmp}-I_{mmp}R_s}{R_p}$$

From this equation we can express the parallel resistance:

$$R_p=\frac{A}{B} \tag{18}$$

Where, A and B are given in (19) and (20).

$$A=R_s\left(I_{sc}^{*}+I_{mmp}-V_{mmp}\right)\exp\left(\frac{V_{oc}^{*}}{nn_sV_T^{*}}\right)$$

$$-\left(R_s\left(I_{mmp}-V_{mmp}\right)+V_{oc}^{*}\right)\exp\left(\frac{I_{sc}^{*}R_s}{nn_sV_T^{*}}\right) \tag{19}$$

$$+\left(V_{oc}^{*}-I_{sc}^{*}R_s\right)\exp\left(\frac{V_{mmp}+I_{mmp}R_s}{nn_sV_T^{*}}\right)$$

$$B=I_{mmp}\left(\exp\left(\frac{V_{oc}^{*}}{nn_sV_T^{*}}\right)-\exp\left(\frac{I_{sc}^{*}R_s}{nn_sV_T^{*}}\right)\right)$$

$$+I_{sc}^{*}\left(\exp\left(\frac{V_{mmp}+I_{mmp}R_s}{nn_sV_T^{*}}\right)-\exp\left(\frac{V_{oc}^{*}}{nn_sV_T^{*}}\right)\right) \tag{20}$$

In [1], an algorithm is used in order to identify two-parameter model under the STC. Those parameters were R_s and R_p. However, the diode ideality factor is taken as known parameter. As we know that $n\in[1,2]$. Using this algorithm, when this parameter takes all the values included in this interval, the three unknown parameters are calculated by MATLAB implementation as shown in Fig. 6.

Firstly, for each value of n the resistances R_s and R_p are determined under the STC (all the values I_{sc}^{*}, V_{oc}^{*}, I_{mpp} and V_{mpp} are used) in order to obtain a maximum output power equal to that one available in the data-sheet.

Then, the error of current, whose the model causes is evaluated. So, the current I_{PVA} is calculated according to (6) by using the Newton-Raphson method. For a package of measurements, the mean absolute error (*MAE*) is calculated as in (21) and stocked.

$$MAE=\sum_{y=1}^{z}\frac{\left|I_m^y-I_{PVA}{}^{y}\right|}{z} \tag{21}$$

where z is the measured points number, it depends on the measurement period and the sampling step of the dSPACE controller board.

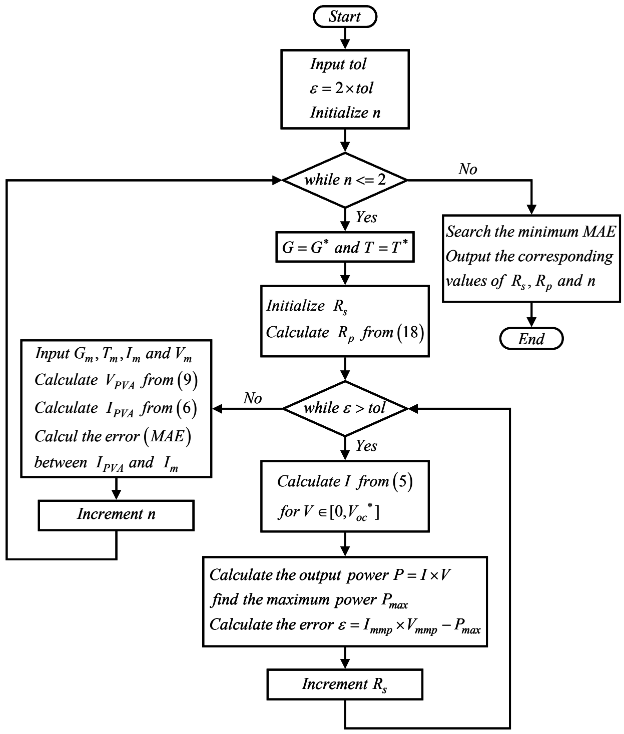

Fig. 6. Algorithm for determination of the PV panel parameters

The best values of the parameters R_s, R_p and n are those for which the model involves the most minimal error. In the beginning of the algorithm, the error (ε) between the calculated and maximum power given by the manufacturer, takes an initial value higher than the tolerance criterion (*tol*) in order to assure the programme running once at least.

B. Determination of the PVA model parameters based on the measurements

The output PVA current carried out by (7) enables us to compute the error committed by the model as follows:

$$r=\sum_{y=1}^{z}\left(I_m^y-I_{PVA}{}^{y}\right)^2 \tag{22}$$

This error represents the objective function, which must be minimised. Since the function (7) is implicit, the calculation of the current I_{PVA} requires an iterative method which imposes a substantial calculating time. Furthermore, this calculation would be repeated for each iteration of the minimisation method. For these reasons and taking into account that $I_{PVA}=I_m$, the function that gives the PVA current is:

$$I_{PVA}=f(G_m,T_m,I_m,V_m,P) \tag{23}$$

Thus, the objective function to be minimised becomes:

$$r=\sum_{y=1}^{z}\left(I_m^y-f(G_m^y,T_m^y,I_m^y,V_m^y,P)\right)^2 \tag{24}$$

Using the MATLAB "lsqcurvefit" function the retained parameters are those which give the better fit of this function.

6. Experimental verification and discussion

Fig. 7 and Fig. 8 show the operating conditions (G_m, T_m) during 8 hours on 20th of November and on 15th of December, 2009, in Compiegne, France. During these measurements, the voltage V_m was settled at 30V. The obtained parameters by both methods are presented in Tables I-II. The current calculated using these parameters is compared with measured one (Fig. 9 and Fig. 10).

The Tables I and II show that the error related to the first method for the two measurements is slightly smaller than those committed with the second one. Furthermore, the parameters values belonging to the same method change according to the operating conditions.

Table III shows the error *MAE* obtained when the current is calculated under operating conditions (measurements on 15th of December) to which the parameters belonged to 20th of November measurements; similarly in the Table IV, made with the measurements recorded on 20th of November.

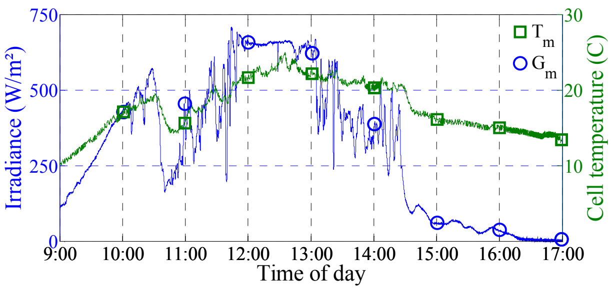

Fig. 7. Operating conditions recorded on 20th of November

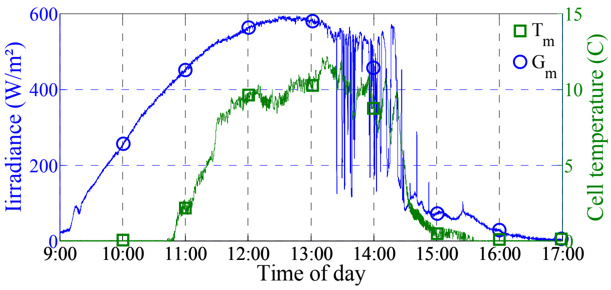

Fig. 8. Operating conditions recorded on 15th of December

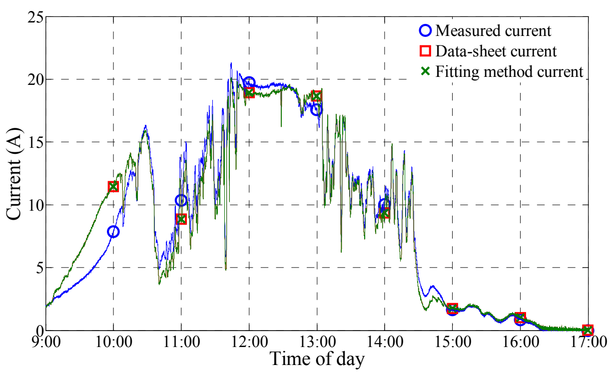

Fig. 9. Current of PVA calculated from data-sheet values and by fitting method versus that measured on 20th of November

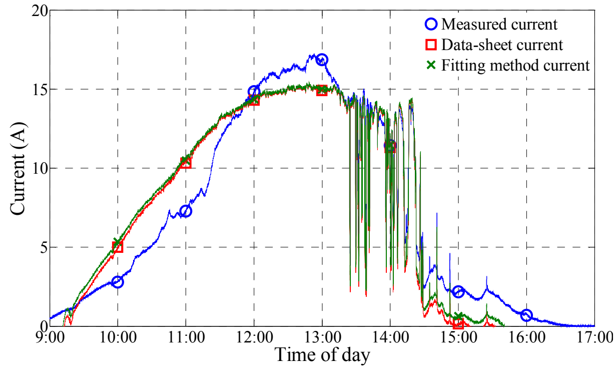

Fig. 10. Current of PVA calculated from data-sheet values and by fitting method versus that measured on 15th of December

Table I. – Parameter Values of PV Panel Derived from the Data-Sheet Values and Related Error for Each Recorded Measurement

PARAMETER AND ERROR *MAE*	MEASURES OF NOVEMBER THE 20th	MEASURES OF DECEMBER THE 15th
n	1.8	1.65
R_s	$1.54.10^{-3}\Omega$	$52.10^{-3}\Omega$
R_p	$4.001.10^{3}\Omega$	$0.121.10^{3}\Omega$
MAE	0.8A	1.407A

Table II. – Parameter Values of PV Panel Derived With the Fitting Approach Method and Related Error for Each Recorded Measurement

PARAMETER AND ERROR *MAE*	MEASURES OF NOVEMBER THE 20th	MEASURES OF DECEMBER THE 15th
n	1.802	1.627
R_s	$0.506.10^{-3}\Omega$	$110.10^{-3}\Omega$
R_p	$156.10^{3}\Omega$	$397.10^{3}\Omega$
MAE	0.84A	1.413A

Table III. – Mean Absolute Error Committed with the Parameters Determined on November 20 under Operating Conditions Taken on December 15

PARAMETERS OF 20/11/2009			*MAE*
n	R_s (Ω)	R_p (Ω)	(A)
1.8	$1.54.10^{-3}$	$4.001.10^{3}$	1.536
1.802	$0.506.10^{-3}$	156.10^{3}	1.533

Table IV. – Mean Absolute Error Committed with the Parameters Determined on December under Operating Conditions Taken on November 20

PARAMETERS OF 15/12/2009			*MAE*
n	R_s (Ω)	R_p (Ω)	(A)
1.65	52.10^{-3}	$0.121.10^{3}$	0.92
1.627	110.10^{-3}	397.10^{3}	0.81

Even that the parameters related to the fitting method give a little smaller error than those resulted using the data-sheet parameters values, and the calculation time is shorter than the time elapsed while the data-sheet algorithm is running, the quality of the minimisation by the MATLAB function "lsqcurvefit" depends on the initial values, lower and upper limits.

Thus, the model is not robust and could lead to some wrong predictions of PVA behaviour. A bad conclusion may be drawn if the model built on the parameters resulted for a measurement, is tested under different conditions.

As in our research work, we don't need to use the PVA model in real time, the model identified using the data-sheet algorithm is simple and can be suitable to modelling the behaviour of PVA under all the operating conditions.

7. Conclusion

The study of the semi-isolated and safety network for the self-feeding building with renewable electricity, especially generated by a PVA, requires a model that allows knowledge of the PVA behaviour under various meteorological conditions.

This paper aims to identify numerical and experimental parameters of the one diode model PV cell extended for a PVA. Using the data-sheet values and one of least squares fitting methods, the error between the calculated and measured current of the output PV array, is minimised. Under various meteorological conditions, based on the carried out parameters, the two methods are compared in regarding to error between the calculated and measured output PVA current, calculation time and easiness of implementation. The method based on the data-sheet values is more appropriate to identify the PVA model parameters

References

[1] M.G. Villalva, J.R. Gazoli and E.R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Array", IEEE Trans on Power Electronics, Vol. 24, n°5, pp. 1198-1208, May 2009

[2] A.N. Celik and N. Acikgoz, "Modelling and experimental verification of the operating current of mono-crystalline photovoltaic modules using four- and five-parameter models", Applied Energy, Vol. 84, n°1, 2007, pp. 1-15.

[3] V. Autier, V. Molcrette and H. Roisse, "Contribution to the determination of the elements of photovoltaic panel (PV) equivalent electric model. Application in the maximal power point (MPP) available analytical expression", in Proc. ICREPQ2003.

[4] M.C. Di Piazza, A. Ragusa and G. Vitale, "Identification of Photovoltaic Array Model Parameters by Robust Linear Regression Methods", in Proc. ICREPQ2009.

[5] E. Karatepe, M. Boztepe and M. Colak, "Development of a suitable model for characterizing photovoltaic arrays with shaded solar cells", Solar Energy, Vol. 81, n°8, pp. 977-992, 2007.

[6] O. Gergaud, B. Multon and H. Ben Ahmed, "Analysis and Experimental validation of various photovoltaic system models", in Proc. 7th International ELECTRIMACS, Montréal, August, 2002.

[7] T. Tafticht, K. Agbossou, M.L. Doumbia and A. Chériti, "An improved maximum power tracking method for photovoltaic systems", Renewable Energy, Vol. 33, pp. 1508-1516, 2008.

[8] D. Sera, R. Teodorescu and P. Rodriguez, "PV panel model based on data-sheet values", in Proc. International Electronics, ISIE, Vigo, Spain, 2007.