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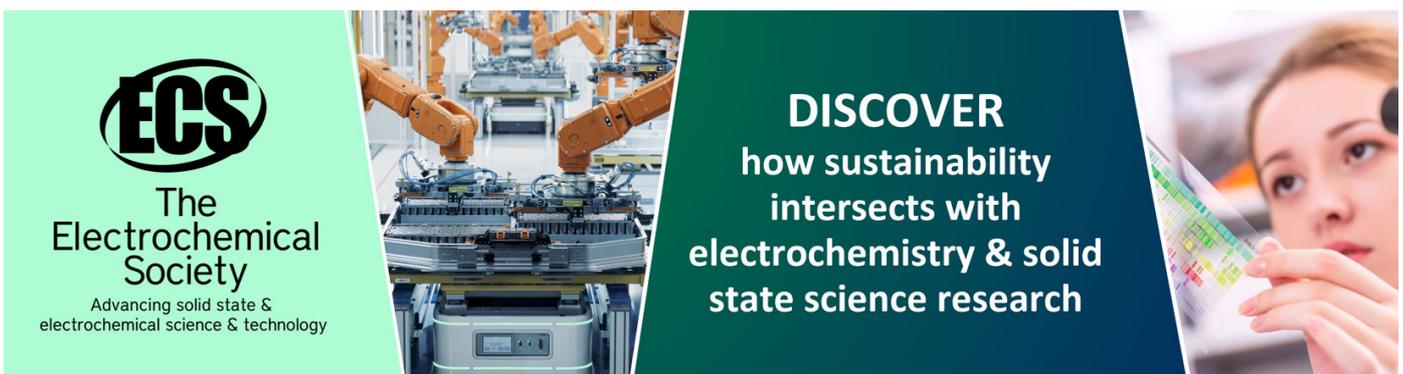
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Experimental validation of a photovoltaic panel model

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Abstract. For operation optimizing, it's important to have internal parameters of a photovoltaic (PV) panel. Experimental measurements were carried out, in order to determine a PV panel internal parameters. From simple measurements, two resistances values: series R_s and shunt R_{sh} have been determined. The two experimental characteristics I-V and P-V have been plotted. And afterward, the system operation has been simulated in Matlab Simulink, to validate the model. Otherwise, PV current equation resulting from the PV cell model has been used to determine 5 parameters. A Matlab program has been developed with the function "fsolve" for solving the system of five equations with five unknowns. Theoretical values were compared with experimental results.

1. Introduction

Electricity needs in the world are constantly increasing at the rate of industrialization and the improvement of people's level of living. In face of this, the climate issue implies an increasingly clean electricity production.

However, the solution can no longer go only through the centralized production of electricity. It must also concern the decentralized production of renewable energy. Photovoltaic has a great potential, among the sources of renewable energy. In fact, the demand for solar energy has increased by 20% to 25% over the past 20 years [1].

In order to improve the use of photovoltaic systems, there are research activities to reduce their costs and improve their efficiency and reliability.

A PV panel in our laboratory will be used to determine by measurements the internal parameters. After that, theoretical characteristics will be validated.

Starting with experimental measurements to determine two resistances values: R_s and R_{sh} of the equivalent electrical circuit. Then, two theoretical characteristics P-V and I-V will be plotted in Matlab Simulink environment using values found in the experimentation. Afterward, the experimental characteristics P-V and I-V will be plotted to validate simulation results.

To be sure of experimental results, a program on Matlab with "fsolve" function will be created, to solve PV current equation for determining the PV panel parameters [11]. The equation has been obtained from the equivalent electrical circuit of a PV cell model, it's a nonlinear equation. A system will be created by repeating this equation five times according to voltage and current measurements. With the "fsolve" function, we will determine five parameters (R_s , R_{sh} , A, T, and I_{sat}) from the system. Finally, a comparison between theoretical and experimental results will be presented.



2. Modeling

PV cells convert sunlight directly into electricity. When the photons of the sun reach the cell, it releases electrons from the negative layer. This electron moves to the positive layer, which gives an electrical current.

Theoretically, the voltage generated by a PV cell is between 0.5 and 0.8 volts, depending on the semiconductor technology. This voltage is very low; this is why several PV cells are made in series or in parallel. The voltage is increased if cells are connected in series and current if they are connected in parallel.

The parameters of a monocrystalline PV panel have been used [2], with 36 cells connected in series and Table 1 shows the characteristics of this panel. The model used in the simulation is PM0115.

Table 1: Photovoltaic panel feature

Characteristic	Value
Maximum power	115 Watt
Voltage at maximum power	17,7 V
Current at maximum power	6,5 A
Open Circuit Voltage	21,6 V
Short circuit current	6,96 A
Tolerance	±5%

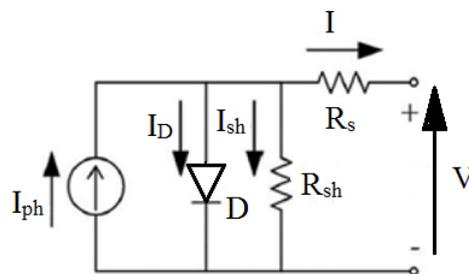


Figure 1. Equivalent electrical circuit of a PV cell

It is possible to represent a cell PV with an electrical equivalent circuit in Figure 1. It consists of a shunt resistance, a series resistance, a diode and a current source [3], [4] and [5].

To implement this PV cell model in simulation software, the following values should be known: Series Resistance R_s , shunt resistance R_{sh} , saturation current I_0 , ideality factor of junction A and temperature T . The manufacturer's values have been taken for I_0 and A . Then experimental measurements were done to determine R_s and R_{sh} .

3. Experimental measurements

The series resistance of the PV cell is very low [6], and its value can influence the variation on the output of PV cells [7], it causes the deviation of the maximum power point.

The shunt resistance of any PV cell should be large enough for higher output power. In fact, if the shunt resistance is low, it will be a higher power loss.

Experimental measurements have been made to determine the two resistances R_s and R_{sh} , the measurements were carried out so rapidly to consider temperature as constant.

To determine the series resistance R_s , the Figure 2 scheme has been used, which consists of a DC generator, a variable resistance, an ammeter and a voltmeter. The PV panel was fully covered with paper to have: $I_{ph} = 0$.

3.1 Measurement of R_s

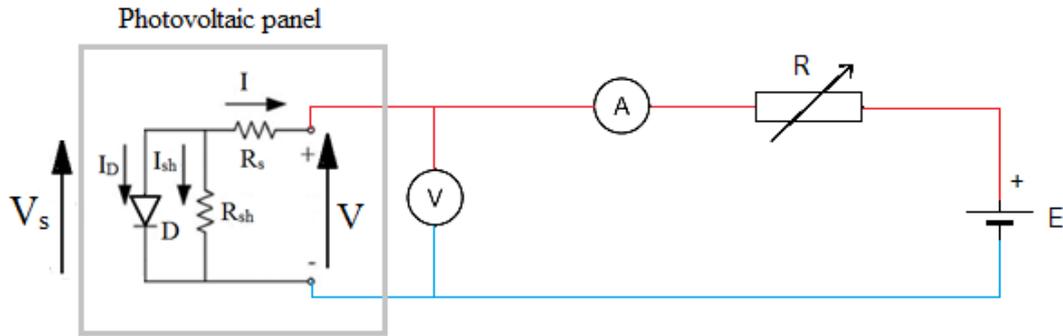


Figure 2. Experimental scheme for determining R_s

By decreasing the variable resistance, the values have been taken of voltage and current and the values are presented in Table 2.

Table 2: Experimental measurements

V (V)	13.6	15.3	16.1	17	18	19	19.2	20	20.95	21.4	22	22.6
I (A)	-0.01	-0.02	-0.03	-0.05	-0.1	-0.2	-0.3	-0.5	-1	-1.5	-2	-3

According to the electrical wiring in Figure 2:

$$R_s = \frac{V - V_s}{I} \quad (1)$$

To determine V_s , the curve I-V characteristic has been plotted using TABLE 2 values and it is presented in Figure 3. This curve is likewise the diode characteristic. The extrapolation of the linear part of the curve gives the V_s value.

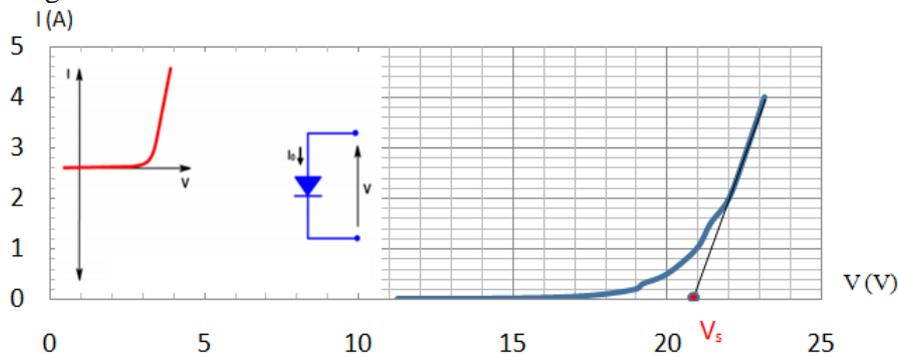


Figure 3. Curve I-V

For 36 cells, $V_s = 20.8V$.

$R_{s,36}$ for 36 cells is calculated by:

$$R_{s,36} = \frac{\Delta V}{\Delta I} = \frac{23,15 - 22,6}{4 - 3} = 0,55\Omega \quad (2)$$

And to calculate R_s for one cell, it is enough to divide by 36:

$$R_s = 0,015\Omega$$

3.2 Measurement of R_{sh}

The same previous electrical scheme will be used but the terminals of the DC generator were inverted, then this wiring presented in Figure 4 will be used. The diode is blocked in this case.

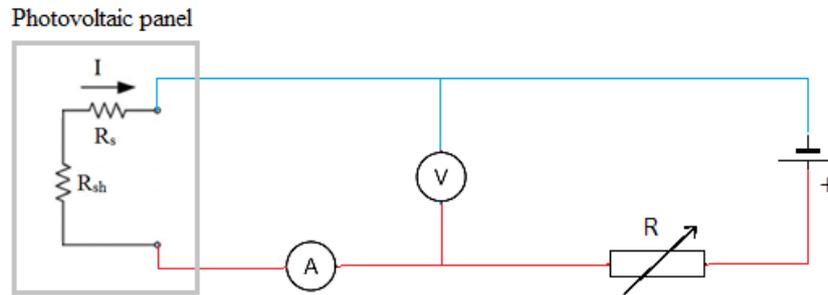


Figure 4. Experimental scheme to determine R_{sh}

According to the Law of Mail:

$$R_{sh_36} + R_{s_36} = \frac{V}{I} \quad (3)$$

Then an electrical measurement is taken: $V = 50 \text{ V}$ and $I = 250 \mu\text{A}$. So:

$$R_{sh_36} + R_{s_36} = 200 \text{ k}\Omega$$

For one cell:

$$R_{sh} \approx 5550 \Omega$$

4. Simulation

From the equivalent circuit of a PV panel represented in Figure 1, the following equations are deduced [8], [9] and [10]:

$$I = n_p I_{ph} - n_p I_{sat} \left(\exp \left(\left(\frac{q}{AKT} \right) \left(\frac{V}{n_s} + R_s I \right) \right) - 1 \right) \quad (4)$$

$$I_{ph} = (I_{sso} + k_i(T - T_r)) \frac{S}{1000} \quad (5)$$

$$I_{sat} = I_{rr} \left(\frac{T}{T_r} \right)^3 \exp \left(\left(\frac{qE_{gap}}{kA} \right) * \left(\frac{1}{T_r} - \frac{1}{T} \right) \right) \quad (6)$$

Where the Table 3 presents the values of measured parameters and Table 4 presents the values of the characters in the equation 4.

Then, these equations are used to do simulation on Simulink with the internal parameters found in the experimental measurements and the manufacturer's values.

Table 3: measured parameters

Symbol	Description	Value
T	Surface temperature of the panel	303° K
R_s	Series resistance of the PV cell	0,015 Ω
R_{sh}	Parallel resistance of the PV cell	5500 Ω

Table 4: parameters values

Symbol	Description	Value
q	Electron charge	1.602×10^{-19} C
A	Ideality factor	1.74
k	Boltzman constant	1.38×10^{-23} j/K
I_{SSO}	Short-circuit current	6.96 A
k_i	SC current temperature coefficient	1.7×10^{-3}
T_r	Reference temperature	298.13 °K
I_{rr}	Reverse saturation current at T_r	2.0793×10^{-6} A
E_{gap}	Energy of the band gap for Silicon	1.1 eV
n_p	Number of cells in parallel	0
n_s	Number of cells in series	36
S	Solar radiation level	0 ~ 1000 W/m ²
I_{ph}	Photocurrent	
I_{sat}	Module reserve saturation current	
S	Solar radiation level	1000 W/m ²

5. Programming

To validate in a second way the values found in the experimental part and to give the study more accuracy, a program under Matlab software have been created with "fsolve" function to determine the values of the internal panel: R_s , R_{sh} , T , A and I_{sat} .

Matlab's "fsolve" subroutine is very effective in solving the nonlinear equations. Thus, the proposed method is user-friendly, with the use of initial values for to start the simulation.

Equation (4) has been used for a single cell, and also under the same conditions in the experimental measurements by covering the PV panel, so $I_{ph} = 0$ and the equation becomes:

$$-I_{sat} \left(\exp \left(\frac{q(V + R_s I)}{AKT} \right) - 1 \right) - \frac{V + R_s I}{R_{sh}} - I = 0 \quad (7)$$

The values of experimental measurements of voltage and current have been used, and five measurements were taken to create a system (8) of five equations:

$$\begin{cases} -I_{sat} \left(\exp \left(\frac{q(V_1 + R_s I_1)}{AKT} \right) - 1 \right) - \frac{V_1 + R_s I_1}{R_{sh}} - I_1 = 0 \\ -I_{sat} \left(\exp \left(\frac{q(V_2 + R_s I_2)}{AKT} \right) - 1 \right) - \frac{V_2 + R_s I_2}{R_{sh}} - I_2 = 0 \\ -I_{sat} \left(\exp \left(\frac{q(V_3 + R_s I_3)}{AKT} \right) - 1 \right) - \frac{V_3 + R_s I_3}{R_{sh}} - I_3 = 0 \\ -I_{sat} \left(\exp \left(\frac{q(V_4 + R_s I_4)}{AKT} \right) - 1 \right) - \frac{V_4 + R_s I_4}{R_{sh}} - I_4 = 0 \\ -I_{sat} \left(\exp \left(\frac{q(V_5 + R_s I_5)}{AKT} \right) - 1 \right) - \frac{V_5 + R_s I_5}{R_{sh}} - I_5 = 0 \end{cases} \quad (8)$$

Table 5 presents the five measurements of voltage and current used in the program:

Table 5: measurements used in the programme

	1	2	3	4	5
V (V)	13.6	16.1	19	21.4	23.15
I (A)	- 0.01	- 0.03	- 0.2	- 1.5	- 4

6. Results and discussions

To determine the two experimental characteristics of the PV panel I-V and P-V, the Figure 5 scheme have been used, which consists of a variable resistance, an ammeter and a voltmeter. The PV panel was illuminated by a projector then the power produced is very low.

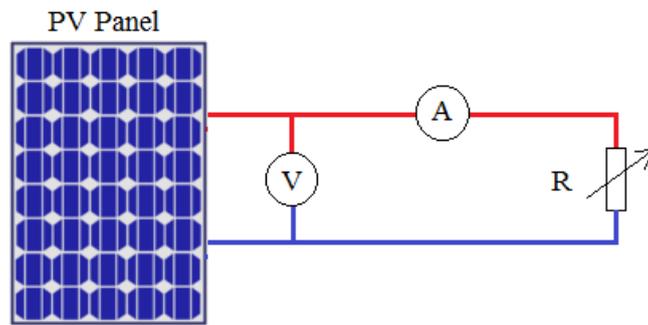


Figure 5. Experimental scheme to determine experimental I-V and P-V

By decreasing the variable resistance we have plotted two experimental characteristics I-V and P-V presented in a. and b. successively in Figure 6.

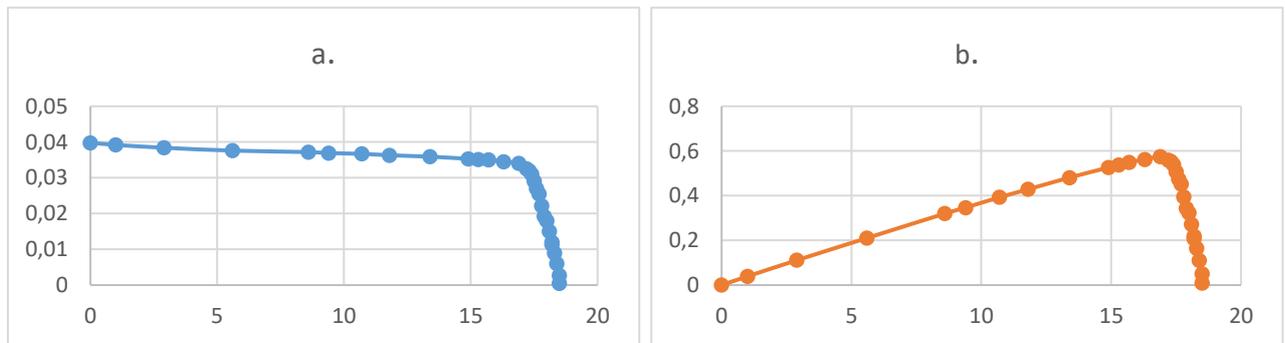


Figure 6. Experimental characteristics a. I-V and b. P-V

The simulation of the PV panel model on Simulink software was done and figure 7 presents two characteristics I-V and P-V of this PV panel. The results found are exactly what we have in the nameplate presented in table 1.

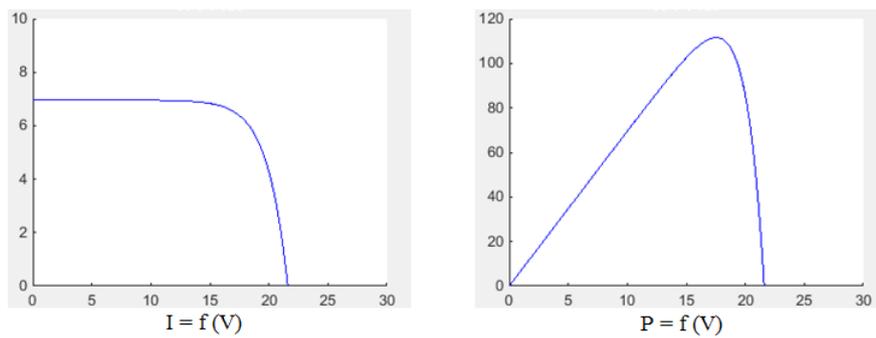


Figure 7. Characteristics of the PV panel

The results of the programming are presented in table 6:

Table 6: Program simulation results

Theoretic data	Measurements data
$R_s = 0.016 \Omega$	$R_s = 0.015 \Omega$
$A = 1.733$	$A = 1.74$
$T = 304.143^\circ\text{K} = 29,008^\circ\text{C}$	$T = 27^\circ\text{C}$
$R_{sh} = 5548.210 \Omega$	$R_{sh} \approx 5550 \Omega$
$I_0 = 2.44953e-06 \text{ A}$	$I_0 = 4.842 \times 10^{-6} \text{ A}$

The results of the simulation and measurement are very close, which gives our study more accuracy.

7. Conclusion

In this paper, experimentally internal resistances of a PV panel have been determined: series and shunt resistances.

The PV panel was simulated using Simulink to determine theoretical I-V and P-V characteristics.

Also Experimental characteristics of the PV panel: I-V and P-V were plotted.

In order to determine all internal characteristics, a program on Matlab with “fsolve” function have been created to solve the nonlinear equation. With “fsolve” function, parameters (R_s , R_{sh} , A , T , and I_{sat}) from a system of five equations have been determined. The system is obtained from experimental measurements, by using the values of the voltage and current.

Finally, theoretical results are very close to the experimental values.

Acknowledgment

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