MODELLING AND SIMULATION OF PHOTOVOLTAIC SOLAR PANEL

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ABSTRACT

In this article, we present a new approach for estimating the one-diode model parameters of a photovoltaic panel according to the irradiance and temperature. These parameters are given from the knowledge of three operating points: short-circuit, open circuit, and maximum power.
In the first step, the adopted approach concerns the resolution of the system of equations constituting the three operating points to write all the model parameters according to series resistance. Secondly, we make an iterative resolution at the optimal operating point by using the Newton-Raphson method to calculate the series resistance value as well as the model parameters. Once the last ones are identified, we consider other equations for taking into account the irradiance and temperature effect.
The simulation results show the convergence speed of the model parameters and the possibility of visualizing the electrical behaviour of the panel according to the irradiance and temperature. With the identified model, we can develop algorithms of maximum power point tracking, and make simulations of PV systems.

INTRODUCTION

In late years, the problem of energy crunch is more and more aggravating. Very much exploitation and research for power energy are proceeded around the world. In particular, the solar energy attracts lots of attention. The utilization of photovoltaic conversion energy is today an emerging technology, characterized by gradually declining costs and increasing acquaintance with the technology.
Solar cells represent the fundamental power conversion unit of a photovoltaic system and are usually arranged in a PV array. For this last, the most important information needed from the manufacturer are the module short circuit current, open circuit voltage, and maximum power point current and voltage, all measured at the same irradiance and cell temperature. This information fixes three current-voltage (*I-V*) points, all of which must lie on the same *I-V* curve and therefore, satisfy the same *I-V* equations. Both of these equations are implicit and nonlinear and therefore determination of analytical solution is difficult.
This paper concerns the resolution of the *I-V* equations for on the one hand identifying the PV panel parameters, and, on the other hand, to predict its behaviour under varying conditions such as irradiance and temperature.

MATHEMATICAL MODEL FOR A PHOTOVOLTAIC CELL

For modelling the PV solar panel, one of the two standard models: the one-diode model or the two-diode model was used to describe the electrical characteristics of solar cell. Each model establishes relations to evaluate the current and the voltage according to the irradiance and temperature.

The double-exponential model (with two diodes) is derived from the physics of the p-n junction and is generally accepted as reflecting the behaviour of such cells, especially those constructed from polycrystalline silicon. It is also suggested that cells constructed from amorphous silicon, usually using thick-film deposition techniques, do not exhibit as sharp a knee in the curve as do the crystalline types, and therefore the one exponential model (with one diode) provides a better fit to such cells [1].

In this work, we consider a prior the one-exponential model. The equivalent circuit used is shown in Fig. 1.

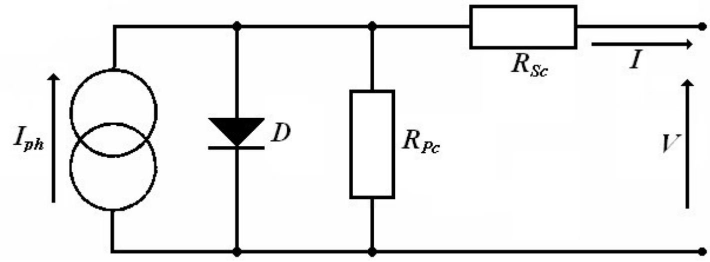

Fig. 1: Cell equivalent circuit (one-exponential model).

The relationship between voltage V [V] and current I [A], for the one-exponential model, is given by the following equation:

$$I = I_{ph} - I_S \left(\exp\left(\frac{q\left(V + R_{Sc} I\right)}{\alpha k T} \right) - 1 \right) - \frac{V + R_{Sc} I}{R_{Pc}} \quad (1)$$

Where R_{Sc} is the series resistance parameter of the cell [Ω], R_{Pc} is the shunt resistance parameter [Ω], α is diode parameter (usually $\alpha \approx 1.2$), T is the cell temperature [K], q is the charge of an electron (1.6021×10^{-19} C), k is the Boltzmann Constant (1.3854×10^{-23} JK^{-1}), I_{ph} is the photo-current [A] and I_S is the saturation current [A].

IRRADIANCE AND TEMPERATURE EFFCETS

The I-V characteristic of a solar cell is also influenced by the temperature of the cell. In this work, the cell temperature is calculated by a simplified linear function between the cell temperature and the irradiation G [Wm^{-2}]. Equation (2) below describes the model, where the temperature T_a determines the crossing point of the function on the vertical axis [3]:

$$T = T_a + 0.03 \cdot G \quad (2)$$

The photo-current I_{ph} is given by:

$$I_{ph} = \left(C_0 + C_1 \cdot T\right) \cdot \frac{G}{G^*} \quad (3)$$

Where C_0 is a coefficient which relate the photo-current to the irradiance [A], C_1 is a coefficient which expresses the relation between the photo-current and the temperature [AK^{-1}], and G^* is the irradiation at the reference conditions [Wm^{-2}].

The constants C_0 and C_1 are expressed by the following equations:

$$C_0 = \frac{I_{SC1} \cdot T_2 - I_{SC2} \cdot T_1}{T_2 - T_1} \quad (4)$$

$$C_1 = \frac{I_{SC2} - I_{SC1}}{T_2 - T_1} \quad (5)$$

Where I_{SC1}, I_{SC2} are the short-circuit currents given respectively at the measured temperatures T_1 and T_2.
The dependence of the saturation current on temperature is given by:

$$I_S = C_3 \cdot T^3 \cdot \exp\left(\frac{-C_2}{T}\right) \quad (6)$$

Where the constants C_2 and C_3 are expressed by the following equations:

$$C_2 = \frac{q \cdot E_g}{k} \quad (7)$$

$$C_3 = \frac{I_{SC1} \cdot \exp\left(\frac{q \cdot E_g}{\alpha k T_1}\right)}{T_1^3 \cdot \left(\exp\left(\frac{q \cdot V_{OC1}}{\alpha k T_1}\right) - 1\right)} \quad (8)$$

Where E_g is the band gap voltage.
Using equation (1), the one-exponential model of the PV array is given as follows:

$$I = I_{ph} - I_S\left(\exp\left(\frac{q(V + R_S I)}{N_C \alpha k T}\right) - 1\right) - \frac{V + R_S I}{R_P} \quad (9)$$

Where R_S is the series resistance parameter of the array [Ω], R_P is the shunt resistance parameter [Ω] and N_C is the number of cells in series.
The set of model parameters (I_{ph}, I_S, R_S and R_P) allows thereafter the layout of the current-voltage curve for different conditions of solar radiation.
The operation point of the PV panel is given by:

$$\begin{cases} V_{panel} = N_S \cdot V \\ I_{Panel} = N_P \cdot I \end{cases} \quad (10)$$

Where N_S is the number of arrays in series and N_P is the number of arrays in parallel.

MODEL PARAMETERS IDENTIFICATION

We remind that the one-exponential model is nonlinear and implicit. Its parameters are given from the knowledge of three operating points: short-circuit, open circuit, and maximum power. In the first step, the adopted approach concerns the resolution of the system of equations constituting the three operating points to write all the model parameters according to series resistance. Secondly, we make an iterative resolution at the optimal operating point by using the Newton-Raphson method to calculate the series resistance value as well as the model parameters.
Notice that a particular attention must be considered for the correct choice of the initial values. Since the inadequate choice of the last ones will have as consequence the divergence of the algorithm. For the series resistance R_S, we suppose that initially it is null:

$$R_{S0} = 0 \quad (11)$$

This allows only the launching of the calculation algorithm of the I_{ph}, I_S, R_S and R_P parameters. If these parameters are known, we can determinate from equation (9) the current I of the PV array according to the voltage V.

Usually, the three operating points given by the manufacturer of the PV array are:

1. Open circuit point:
   $I = 0 \quad \& \quad V = V_{OC}$
2. Short-circuit point:
   $I = I_{SC} \quad \& \quad V = 0$
3. Optimal operating point (at maximum power):
   $I = I_{OP} \quad \& \quad V = V_{OP}$

In compact form and after some developments, we can write by taking into account the last three operating points the following system:

$$\begin{bmatrix} I_{ph} \\ I_S \\ R_P^{-1} \end{bmatrix} = [M]^{-1} \cdot \begin{bmatrix} 0 \\ I_{SC} \\ I_{OP} \end{bmatrix} \tag{12}$$

The matrix M is related to R_S, V_T, V_{OC}, I_{SC}, V_{OP} and I_{OP}, and it is given by:

$$[M] = \begin{bmatrix} 1 & -C & -V_{OC} \\ 1 & -B & -R_S I_{SC} \\ 1 & -A & -V_{OP} - R_S I_{OP} \end{bmatrix} \tag{13}$$

Where A, B and C are respectively expressed by the following equations:

$$A = \exp\left(\frac{q(V_{OP} + R_S I_{OP})}{N_C \alpha k T} \right) - 1 \tag{14}$$

$$B = \exp\left(\frac{q R_S I_{SC}}{N_C \alpha k T} \right) - 1 \tag{15}$$

$$C = \exp\left(\frac{q V_{OC}}{N_C \alpha k T} \right) - 1 \tag{16}$$

Substituting the inverse of the matrix M into equation (12), we can write:

$$\begin{cases} I_{ph} = \dfrac{V_{OC} I_{SC} A - V_{OC} I_{OP} B - V_{OP} I_{SC} C}{\det_M} \\ I_S = \dfrac{V_{OC} I_{SC} - V_{OC} I_{OP} - V_{OP} I_{SC}}{\det_M} \\ R_P^{-1} = \dfrac{I_{SC} A - I_{OP} B - (I_{SC} - I_{OP}) C}{\det_M} \end{cases} \tag{17}$$

With:

$$\det_M = (V_{OC} - R_S I_{SC}) A + (-V_{OC} + V_{OP} + R_S I_{OP}) B + (-V_{OP} + R_S (I_{SC} - I_{OP})) C \tag{18}$$

To calculate the value of R_S, we must use another equation. The latter is obtained from the derivative of the power. For an optimal operating point, the PV array work at its maximum power and thus the derived power at this point is null. At this point, we can write:

$$\left. \frac{dP}{dV} \right|_{\substack{Optimal \\ operating}} = 0 \;\Rightarrow\; \boxed{\left. \frac{dI}{dV} \right|_{V_{OP}} = -\frac{I_{OP}}{V_{OP}}} \tag{19}$$

From equation (9), the derivative of current can be expressed as below:

$$\frac{dI}{dV} = -\left(R_S + \left(\frac{qI_S}{N_C \alpha kT} \cdot \exp\left(\frac{q(V + R_S I)}{N_C \alpha KT} \right) + \frac{1}{R_P} \right)^{-1} \right)^{-1} \quad (20)$$

Substituting this equation into (19), we define the function *f* as follows:

$$f = I_{OP} - (V_{OP} - R_S I_{OP}) \cdot \left(\frac{qI_S}{N_C \alpha kT} \cdot \exp\left(\frac{q(V_{OP} + R_S I_{OP})}{N_C \alpha kT} \right) + \frac{1}{R_P} \right) = 0 \quad (21)$$

As I_S and R_P are related to R_S, the function *f* is also. The Newton–Raphson method is used for solving the equation $f(R_S) = 0$. Notice that the method is commonly used because its simplicity and great speed.
The derivative of the function *f* is given by the following equation:

$$\begin{aligned} \frac{df}{dR_S} = & -\frac{(V_M - R_S I_M)}{det_M} \frac{qI_M I_{SC}}{N_C \alpha kT} (A - B) + \frac{1}{R_P} \left(I_M + \frac{(V_M - R_S I_M)}{det_M} \frac{d\,det_M}{dR_S} \right) \\ & + \frac{qI_S}{N_C \alpha kT} \exp\left(\frac{q(V_M + R_S I_M)}{N_C \alpha kT} \right) \cdot \left(I_M \left(1 - \frac{q(V_M - R_S I_M)}{N_C \alpha kT} \right) + \frac{V_M - R_S I_M}{det_M} \cdot \frac{d\,det_M}{dR_S} \right) \end{aligned} \quad (22)$$

Where $\det_M$ is the determinant of the matrix *M*; its derivative is given by:

$$\begin{aligned} \frac{d\,det_M}{dR_S} = & \left(\frac{q(V_{OC} - R_S I_{SC}) I_M}{N_C \alpha kT} - I_{SC} \right) A + \left(\frac{q(-V_{OC} + V_M + R_S I_M) I_{SC}}{N_C \alpha kT} + I_M \right) B \\ & + (I_{SC} - I_M) C + \frac{q(V_M I_{SC} - V_{OC}(I_{SC} - I_M))}{N_C \alpha kT} \end{aligned} \quad (23)$$

The developed algorithm can be summarised in the following scheme:

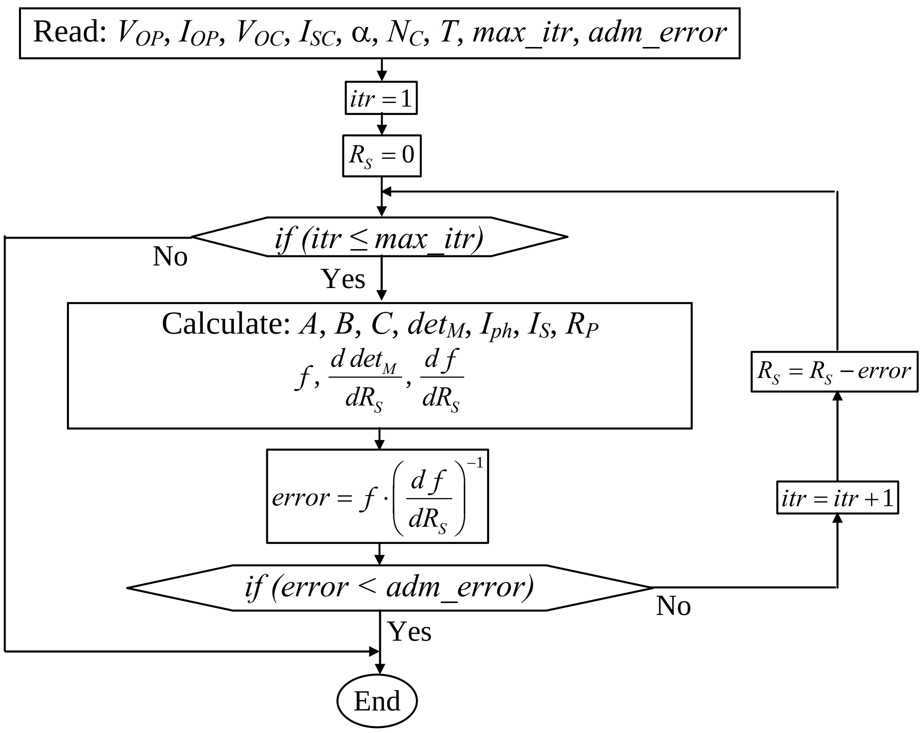

Fig. 2: Design of the developed algorithm.

SIMULATION RESULTS

The electrical specifications of the chosen PV array are given in the following table:

Module Kyocera	Model KC 50
Maximum power	50 W
Maximum power voltage	16.7 V
Maximum power current	3 A
Open circuit voltage	21.5 V
Short circuit current	3.1 A
Number of cells	36

Table 1: Electrical specifications.

These electrical specifications are obtained under test conditions of irradiance of 1 kW/m^2 and cell temperature of 25 °C. Notice, that E_g is equal to 1.12 V.
Once several tests of simulation, the computation solution of the series resistance converges after some iterations in according to the admissible error and the initial value of R_S. For example, the solution converges after three iterations for an admissible error equal to 10^{-3}, and after fourteen iterations for an admissible error equal to 10^{-15}. The following figure show the speed convergence for various initial values of the series resistance R_S.

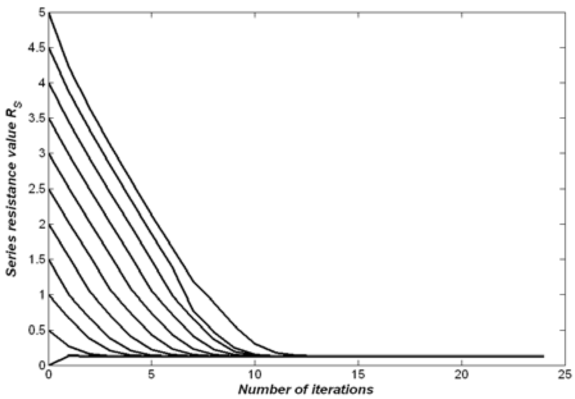

Fig. 3: Speed convergence of the series resistance.

The calculated current-voltage characteristics for the PV array, utilizing the developed algorithm are presented in Fig. 4, for different conditions of solar radiation. In the plot are also indicated the points of maximum power for each irradiance and the lines of constant power.

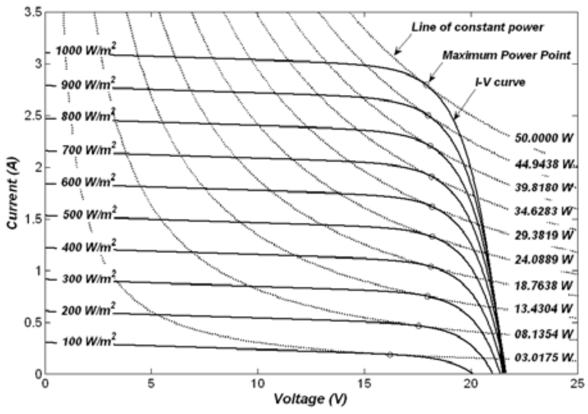

Fig. 4: The simulated *I-V* curves for different irradiation conditions.

According to the previous figure, we notice well that the *I-V* characteristic of the PV array is not stable, and thus, it is strongly related to the irradiance.
The simulated output power curves of the PV array are given as below:

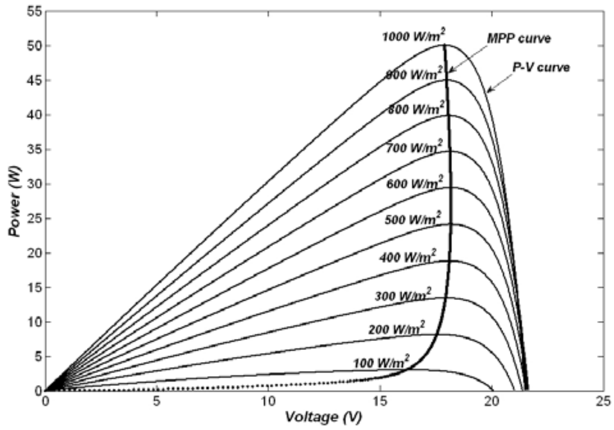

Fig. 5: Output power of the PV array for different irradiances.

For the output power, we note that from certain irradiance the value of the optimal voltage is practically constant.
The effect of the temperature on the electrical behaviour of the PV array is given in the following figures:

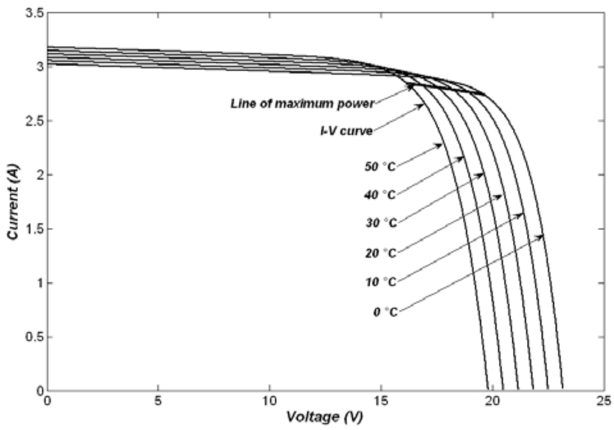

Fig. 6: The simulated *I-V* curves for different temperatures.

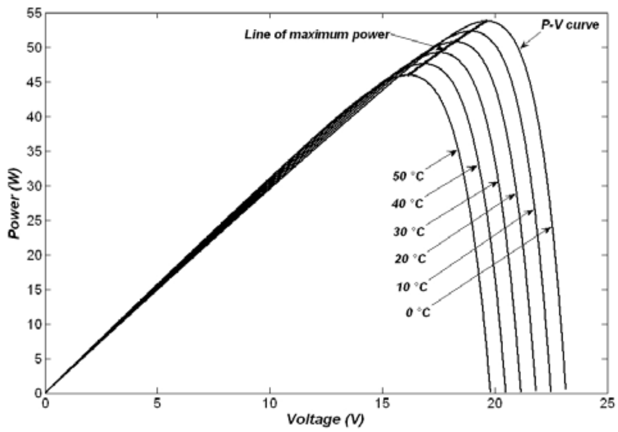

Fig. 7: Output power of the PV array for different temperatures.

We note that the increase in the temperature leads to a small increase in current but an important fall of the voltage, and thus, a fall of the produced power.
In Fig. 6, we show the effect of the irradiance on *I-V* characteristics in 3D representation as well as the line of optimal operating.

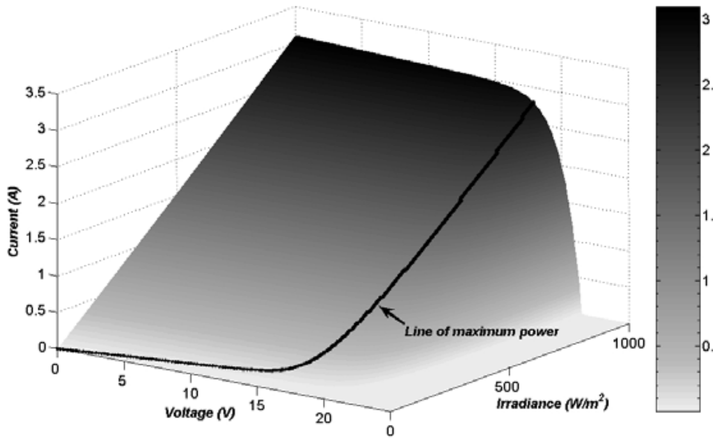

Fig. 8: Current-voltage characteristics in 3D representation.

It should be noted that simulations were led under the Matlab/Simulink environment while considering that the panel contains one module (i.e. $N_S = N_P = 1$).

CONCLUSION

In this article, we presented the modelling and the simulation of the electrical behaviour of a photovoltaic panel according to the irradiance and temperature.
We developed an algorithm for estimating the one-exponential model parameters of the photovoltaic array. These parameters are identified from the knowledge of three operating points given by the manufacturer. The speed convergence of the solution provided by the developed algorithm depends on the choice of the initial value of R_S and the admissible error. Let us note that a sensitivity of the algorithm for the optimal operating point was noted owing to the fact that a small variation of the value of the optimal voltage leads to a very great variation of the values of the identified parameters.
The simulation results showed the effectiveness of the developed algorithm for calculating the model parameters, and the possibility of visualizing the electrical behaviour of the PV panel according to the irradiance and the temperature.

REFERENCES

[1] Gow, J.A. & C.D. Manning, 1999, "Development of a photovoltaic array model for use in power-electronics simulation studies", IEE Proc. Electronics Power Appl., Vol. 146, No. 2, pp. 193-200.

[2] Towsend, T.U., 1989, *A method for estimating the long-term performance of direct-coupled photovoltaic systems*, Thesis of "Master of Science", University of Wisconsin-Madison.

[3] Moraes-Duzat, R., 2000, *Analytical and experimental investigation of photovoltaic pumping systems*, Thesis of "Doktors der Naturwissenschaften", University of Oldenburg-Germany.