

## TWO PHOTOVOLTAIC CELL SIMULATION MODELS IN MATLAB/SIMULINK

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**Abstract-** The study of photovoltaic systems in an efficient manner requires a precise knowledge of the *IV* and *PV* characteristic curves of photovoltaic modules. Therefore, the objective of this paper is to develop two different computer models to simulate the behavior of a photovoltaic cell, to be able to represent these *IV* and *PV* curves. Both models are implemented in Matlab-Simulink. These two models are part of a larger study of different ways to simulate a cell or photovoltaic panel presented in section two. To demonstrate the validity of the models graphs *IV* and *PV* curves resulting with those provided by the manufacturer have been compared. To analyze the operation and the suitability of the model it is necessary to have precise knowledge of these curves. With experimental and technical data of the commercial panel Mitsubishi PV-TD185MF5 will be validated these models.

**Keywords:** Photovoltaic (PV), PV cells, Modeling, Simulation, Matlab/Simulink, *IV* curves.

### I. INTRODUCTION

Photovoltaic solar energy is a clean, renewable, energy with a long service life and high reliability. But because of its high cost and low efficiency, energy contribution is less than other energy sources. It is therefore essential to have effective and flexible models, to enable you to perform easy manipulation of certain data (for example, irradiance and temperature) investigate how to get its performance as maximum as possible. The use of these simple models provides sufficient accuracy to analyze the behavior of the solar cell and have proven to be effective in most cases.

Solar cells convert solar energy into electrical energy. This phenomenon occurs in materials which have the property of capture photon and emit electrons. The main material used in the photovoltaic industry is silicon. But

there are many lines of research to find materials to replace or supplement to silicon to improve conversion efficiency, as for example [12, 13].

The physical principle governing the behavior of a photovoltaic cell, can be explained, based on a p-n junction of a semiconductor material sensitive to sunlight, i.e., the electrical behavior of a PV cell is essentially that of a diode.

The ideal solar cell, theoretically, can be modeled as a current source in anti-parallel with a diode (figure 1). The direct current, generated when the cell is exposed to light, varies linearly with solar radiation. An improvement of the model includes the effects of a shunt resistance and another in series.

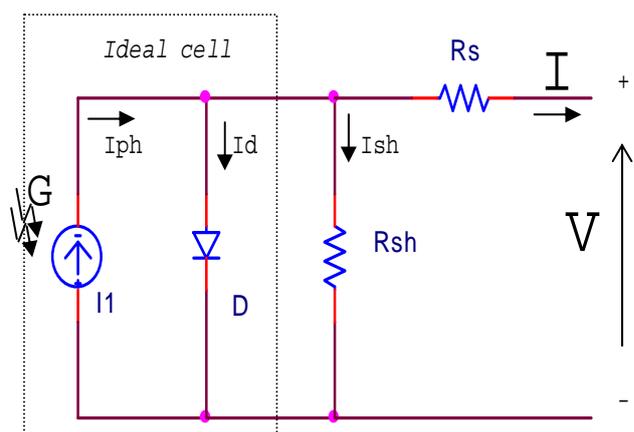


Figure 1. Equivalent circuit for PV modules

According to [4, 14] and based on the equivalent circuit (Figure 1) of a photovoltaic panel its characteristic equation is deduced.

$$I = I_{ph} - I_s \left( e^{\frac{(V + I R_s)q}{akT N_s}} - 1 \right) - \frac{(V + I R_s)}{R_{sh}} \quad (1)$$

This expression describes the electrical behavior and determines the relationship between voltage and current supplied by a photovoltaic module. It is a non-linear mathematical equation whose parameters are,  $N_s$  is number of cells in series,  $I_{ph}$  is the current produced by the photoelectric effect,  $I_S$  is the reverse saturation current.  $R_S$  and  $R_{sh}$  are inherent resistances in series and parallel associated with the cell.  $Q$  is the electron charge,  $k$  Boltzmann's constant and  $a$ , the ideality factor modified.

To determine the behavior of photovoltaic panels it is necessary to know the voltage and current provided by different operating states they can work ( $I$ - $V$  and  $P$ - $V$  curves). An accurate knowledge of the characteristic curves is of vital importance for control and evaluation of solar cell performance. As for example, the  $IV$  and  $PV$  characteristic curves are seen in Figures 2 and 3. The *characteristic curve* is, the relationship between the electric current (power) which provides the cell and the potential difference between its ends, for a given radiation intensity, when the load is being varied.

These characteristic curves also depend on the cell's temperature. These curves are compared with those obtained from computer models based on Equation (1).

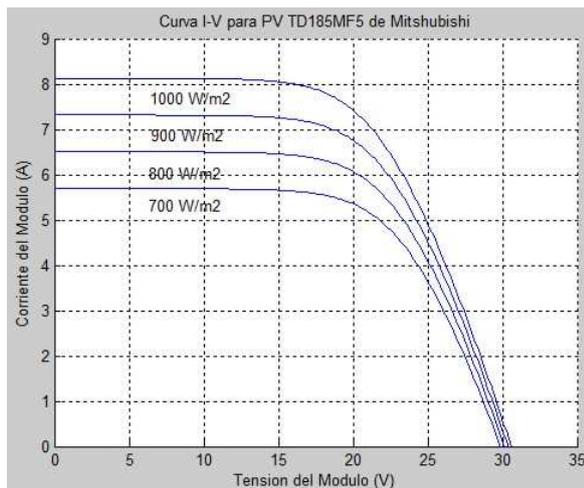


Figure 2. Curve  $IV$  for constant  $T^{\circ}$

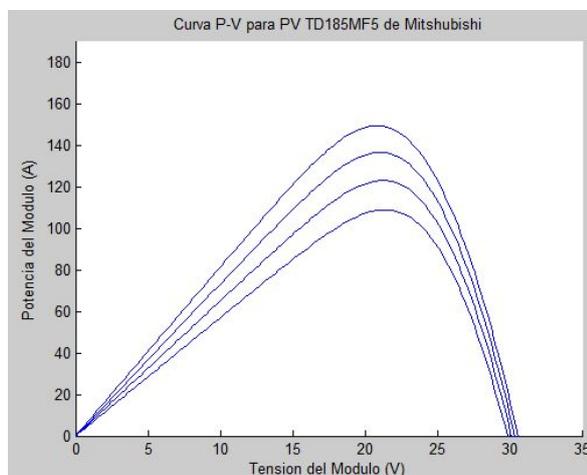


Figure 3. Curve  $PV$  for constant  $T^{\circ}$

Each curve has point of maximum power, which is the optimum operating point. The cell or module must work at this point for an efficient use. Two other important points of this curve are the open circuit voltage ( $V_{oc}$ ) and short circuit current ( $I_{sc}$ ). The open circuit voltage is the maximum voltage that provides the module for zero current (no-load or in vacuum), while the short-circuit current shows the maximum current which is able to provide the module (short circuit load).

### A. Photovoltaic Panel to be Developed

In order to apply these concepts to developments of a solar cell model, the Mitsubishi PV-TD1185MF5 PV module has been chosen for modeling. This module has 50 series connected polycrystalline cells. The key specifications are shown in Table 1.

Table 1. Key specifications of the Mitsubishi PV Panel

Model	PV-TD185MF5
Cell type	Polycrystalline Silicon 156mm x 156mm
Maximum Power [W]	185
Open Circuit Voltage $V_{oc}$ [V]	30.60
Short circuit Current $I_{sc}$ [A]	8.13
Voltage, max power $V_{mpp}$ [V]	24.40
Current, max power $I_{mpp}$ [A]	7.58
Normal operating cell temperature ( $NOCT$ )	47.5 °C

The performance of solar cell is normally evaluated under the standard test condition (STC), where an average solar spectrum at AM 1.5 is used, the irradiance is normalized to  $1000W/m^2$ , and the cell temperature is defined as 25 °C.

## II. TYPE OF MODELS

The two models presented in this paper are part of a more complete study of models of cell or photovoltaic panels. The models that are analyzed and compared differ depending on if they are modeled with Matlab, Simulink or with the support of some of their toolboxes. Below is a brief summary of each of the simulation forms analyzed in this work.

### A. Matlab Programming

This model is made only in Matlab, based on mathematical equations that define the photovoltaic cell. From the work of Walker [6], Gonzalez [7] and Ahikiro [8] a function in Matlab [2] has been developed which calculates the current module from data of voltage, solar radiation and temperature. Setting the constant temperature or radiation, curves  $IV$  and  $PV$  will be obtained. From another script also calculates the maximum power point.

### B. Matlab Tools

This section has taken into account two ways to represent the  $IV$  and  $PV$  curves. In the first form of representation, the graphic interface for curve fitting Cftool (Curve Fitting Toolbox) has been used. The

starting point of this model is the manufacturer's datasheet, in which the  $IV$  and  $PV$  curves of the panel are represented. In this curve at least three coordinates  $(V, I)$  are known,  $(0, I_{sc})$ ,  $(V_{mpp}, I_{mpp})$  and  $(V_{OC}, 0)$ . Manually more coordinates can be approximated to facilitate the representation. With these coordinates, the tool will provide an equation of a similar curve to the original one.

In the second form, the model consists of two Matlab programs. The first serves for the presentation and data capture and calculations are made in the second one. These calculations are based on three functions of MATLAB:  $f_{solve}$ ,  $f_{zero}$  and  $f_{lsqnonlin}$ . In this case the data used were obtained experimentally from the panels analyzed. Data can be exchanged from one form of representation to another.

**C. Basic Model in Simulink**

This model is made based on [5, 9]. It is a model like the one shown in section D, also based on mathematical Equation (1) but made with elements of Simulink. It is a basic model in which the values of  $R_s$  ( $0.001 \Omega$ ) and  $R_{sh}$  ( $1000 \Omega$ ) are assumed to be known.

**D. Simulink Model with Tags**

This is the usual way to model a PV cell that has been developed among other authors, by Villava [3]. It starts from the same equations as in section A, but it is developed in Simulink. Based on this kind of programming could also simulate the basic model of the previous section in this way.

The model developed with tags, presented in this paper (Figures 3 and 4), model in Section C is the basic model based on Equation (1). Therefore the results have to be the same.

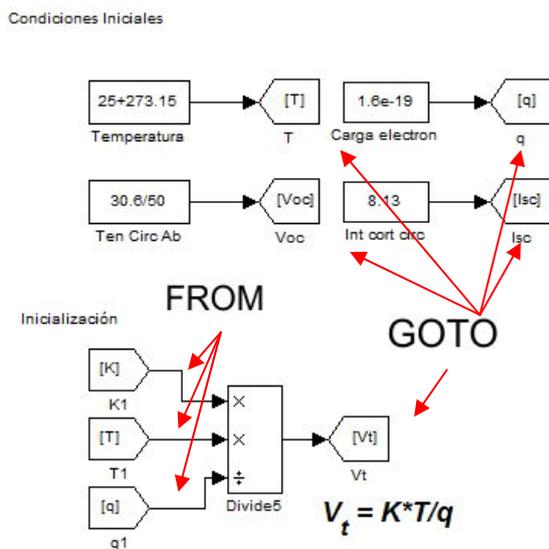


Figure 4. Types of tags

**E. Model of Physical Component**

This model is made from physical elements using Simscape. With those elements, electrical equivalent circuit diagram of the cell is performed. This model is presented in Section IV.

**F. Model of Advanced Component Library**

This is the simplest model. It works with an element of SimElectronics, that is a toolbox dependent of Simscape. The element to model, Solar Cell, appears in the Source Library. Only, it is needed to enter the parameters that define the cell, provided by the manufacturer's data sheet.

**G. Model According with LookTable Function**

This model is created from experimental data of the panel that is going to be simulated. It is based on the element Look Table (2D) Lookup Tables library in Simulink which generates a vector of data, from the experimental data of irradiance, voltage and current. Then use the surface fitting tool. In this case also the simulated photovoltaic panel is Mitsubishi PV-TD185MF5.

**III. MODEL BASED ON SIMULINK WITH TAGS**

In this model two types of tags (Figure 4) were worked with:

- From: Outputs the data type (or types) of the signal connected to the corresponding Goto block. Library: Signal Routing.
- Goto: Pass block input To/From blocks. Input can be of any type. Library: Signal Routing.

From/Goto combinations can be quite powerful in Simulink. These blocks are useful tools to structure a complex design which would otherwise have many crossing signal lines, a stylistic choice that can make a model harder to decipher. But, From/Goto blocks can only be used with a local scope. They are basically non-functional, simply hiding a signal line from view.

The model developed (Figure 5) is based on the equivalent circuit of solar cell (Figure 1) and its characteristic equation, Equation (1). Where current ( $I$ ) obtained in the solar panel is defined by the following expression:

$$I = I_{ph} - I_d - I_{sh} \tag{2}$$

Being  $I_{ph}$ ,  $I_d$  and  $I_{sh}$ :

$$I_{ph} = I_r \cdot \frac{I_{sc}}{I_{r0}} \tag{3}$$

$$I_d = I_s \cdot (e^{\frac{V+I \cdot R_s}{V_t} \cdot n} - 1) \tag{4}$$

$$I_s = I_{sc} \cdot (e^{\frac{V_{OC}}{V_t} \cdot n} - 1) \tag{5}$$

$$V_t = \frac{k \cdot T}{q} \tag{6}$$

The model developed is shown in Figure 5. In this model the irradiance ( $I_r$ ) is a vector of value [200 400 600 800 1000]. It will be represented an  $IV$  characteristic curve for each irradiance value in the same graph, as shown in Figure 6. The same goes for the  $PV$  curve in Figure 7. If 50 cells are put in series a full panel simulation is obtained.

**IV. MODEL BASED ON PHYSICAL COMPONENT**

For this model the starting point is the knowledge of the system. In this case, instead of knowing the mathematical equations the equivalent circuit of the photovoltaic cell is known.

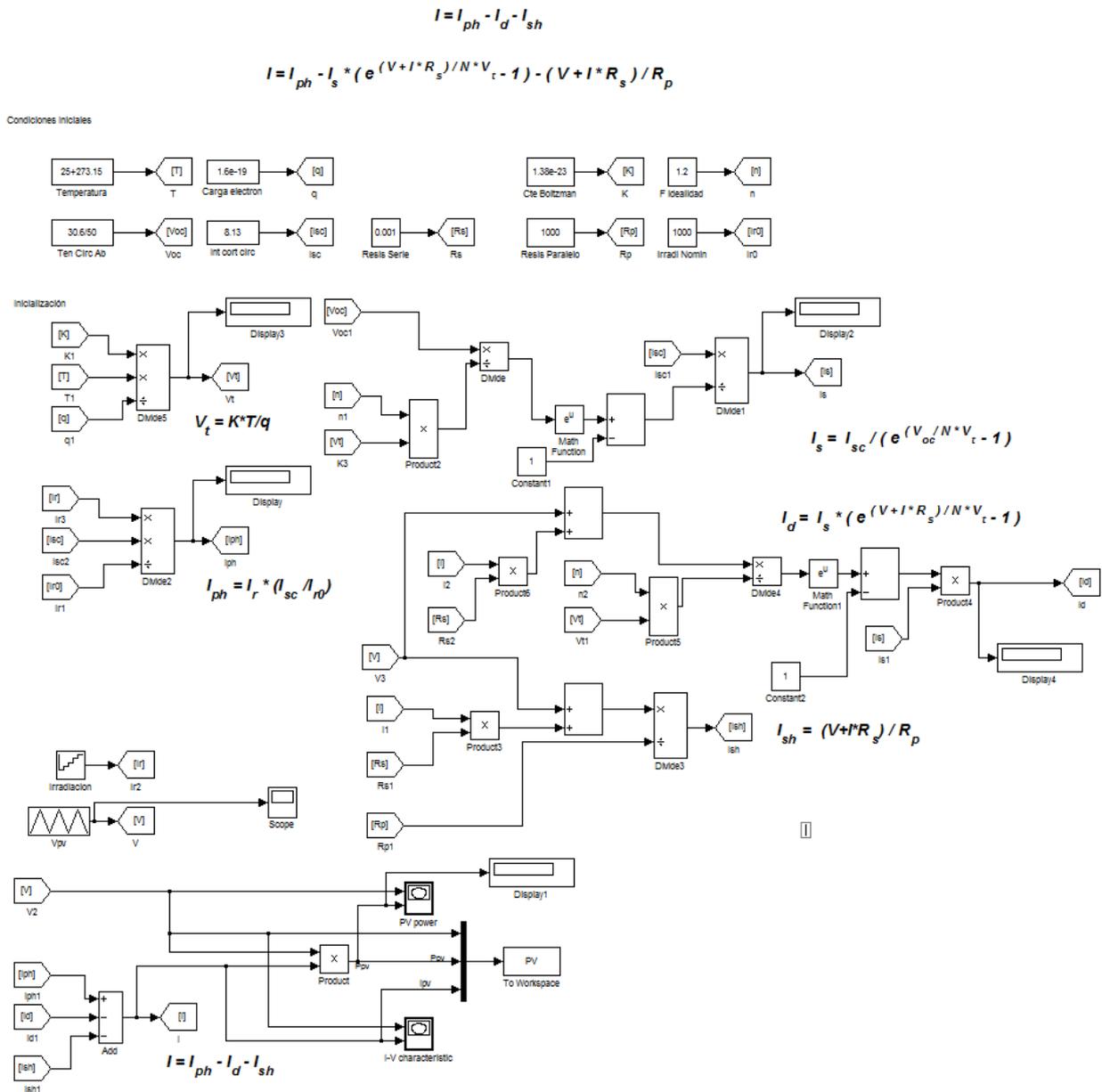


Figure 5. Simulink model with tags

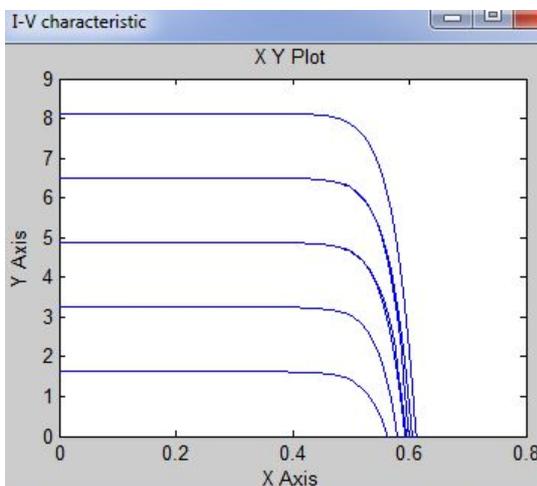


Figure 6. IV Curve results

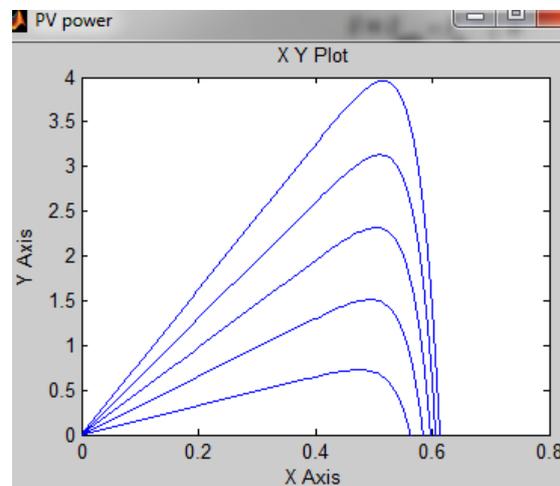


Figure 7. PV Curve results

Equivalent circuit of an ideal solar cell, in theory, can be modeled as a current source in anti-parallel with a diode. An improvement of the model includes the effects of a parallel resistance and another one in series.

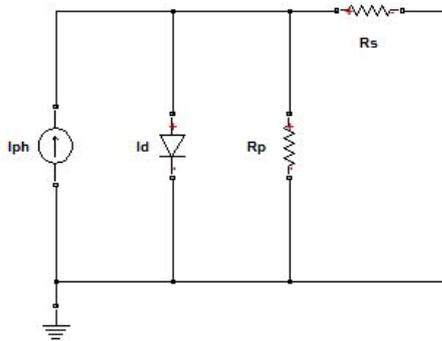


Figure 8. Model of physical component

The model (Figure 8) is developed with Simscape elements. Simscape is a tool of MATLAB/SIMULINK for simulation of physical elements by means of their description of the elements that constitute the circuit.

- $I_{ph}$ : It is a DC current source. Library: Electrical Sources. Electrical → Foundation Library → Simscape
- Diode: The Diode block represents one type of diodes exponential. It's an element of the Electrical Elements library. Electrical → Foundation Library → Simscape
- $R_s$  and  $R_p$ : Resistors which are elements of the Electrical Elements library. Electrical → Foundation Library → Simscape

To define the circuit, must be given values to the four elements that form it:

- $I_{ph}$ : The current source takes the value of the short circuit current of the cell.
- Diode: It is an exponential diode that depends on two vectors. Voltage Vector  $[V_1 V_2]$  and Currents vector  $[I_1 I_2]$
- $R_s$  and  $R_p$ : Some authors [5] give a large value for  $R_p$  (1000  $\Omega$ ) and a small value (0.001  $\Omega$ )  $R_s$ . Other values calculate their values from their definitions [4]. In this work the first case has been chosen, to simplify the model. Figures 9 and 10 show the IV and PV curves obtained with this model, for a panel of 50 cells in series.

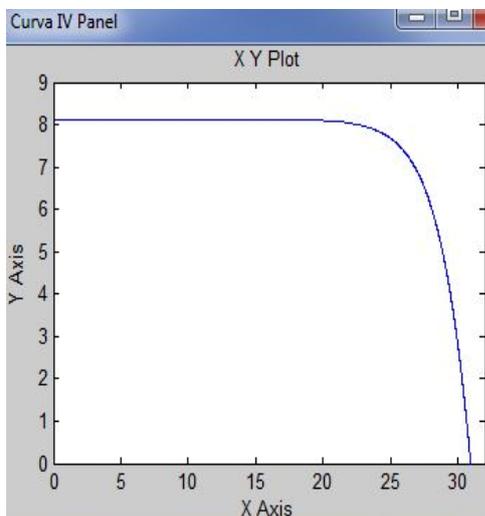


Figure 9. IV Curve results

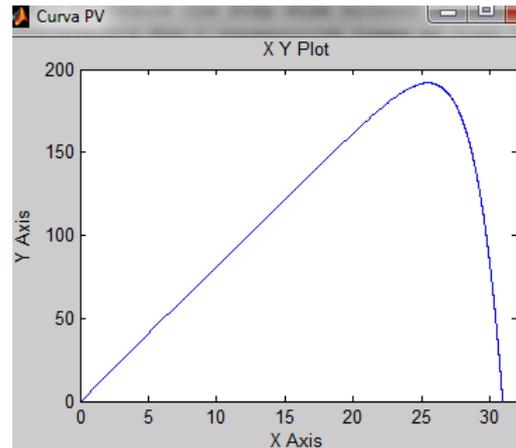


Figure 10. PV curve results

## V. CONCLUSIONS

Since the field tests can be expensive and depend primarily on weather conditions it is very convenient to have simulation models to enable work at any time. For this reason, in this paper, the development of two methods for the modeling of photovoltaic arrays has been analyzed.

Models' aim is to achieve an IV curve similar to the graph that presents the manufacturer's data sheet of the solar panel. The more similar, the better the model will be. In models made, results are similar and in accordance with the wanted results the developed models, although they are simple models, it is possible to study the behavior of photovoltaic cells in the time domain.

Assuming the validity of both models, it is considered that it is easier to make adjustments to the first model than in the second one, because it uses data supplied by the manufacturer. In the second model there is a greater number of assumptions, for example  $I_{ph}$  equates directly to the  $I_{SC}$  which gives the manufacturer. As a continuation of this work, other models proposed in chapter two will be made.

## NOMENCLATURES

- $I_{SC}$ : Short-circuit current
- $I_{mpp}$ : Current at the maximum-power point
- $I_{ph}$ : Light-generated current
- $I_D$ : Diode current
- $I_S$ : Diode reverse saturation current
- $I_{sh}$ : Current through the shunt resistance
- $I_r$ : Irradiation
- $V_{OC}$ : Open-circuit voltage
- $V_{mpp}$ : Voltage at the maximum-power point
- $P_{mpp}$ : Power at the maximum-power point
- $R_s$ : Series resistance
- $R_{sh}$ : Shunt resistance
- $q$ : Electron Charge constant,  $1.6 \cdot 10^{-19}$  C
- $n$ : emission coefficient, ideality factor (Si = 1.2)
- $a$ : diode ideality constant.
- $k$ : Boltzmann's constant
- $T$ : Cell temperature
- $N_s$ : Number of cells in series

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### **REFERENCES**

- [1] J.A. Gow, C.D. Manning "Development of a Photovoltaic Array Model for Use in Power Electronics Simulation Studies", IEE Proceedings on Electric Power Applications, Vol. 146, No. 2, pp. 193-200, March 1999.
- [2] J.A. Ramos, I. Zamora, J.J. Campayo. "Modeling of Photovoltaic Module", International Conference on Renewable Energies and Power Quality (ICREPPQ'10) Granada, Spain, 23-25 March 2010.
- [3] M.G. Villalva, J.R. Gazoli, E. Ruppert "Modeling and Circuit Based Simulation of Photovoltaic Arrays", Brazilian Journal of Power Electronics, Vol. 14, No. 1, pp. 35-45, 2009.
- [4] W. DeSoto, "Improvement and Validation of a Model for Photovoltaic Array Performance", M.Sc. Thesis, Mechanical Engineering, University of Wisconsin, Madison, 2004.
- [5] C. Osorio. Matlab-Simulink models, Mathworks.
- [6] G. Walker, "Evaluating MPPT Converter Topologies Using a Matlab PV Model", Journal of Electrical and Electronics Engineering, Australia, Vol. 21, No. 1, pp. 49-56, 2001.
- [7] F. Gonzaez-Longatt, "Model of Photovoltaic in Matlab<sup>TM</sup>", 2nd Latin American Student Congress of Electrical Engineering and Computer Science (II CIBELEC 2005), Puerto la Cruz, Venezuela, April 2006.
- [8] A. Oi, "Design and Simulation of Photovoltaic Water Pumping System", Master Thesis, California Polytechnic State University, San Luis Obispo, CA, 2005.
- [9] <http://ecee.colorado.edu/~ecen2060/matlab.html>
- [10] A. Luque, S. Hegedus, "Handbook of Photovoltaic Science and Engineering", John Wiley & Sons Ltd., 2003.
- [11] A.S. Golder, "Photovoltaic Generator Modeling for Large Scale Distribution System Studies", Master Thesis, Drexel University, 2006.
- [12] A. Rostami, K. Abbasian, N. Gorji, "Efficiency Optimization in a Rainbow Quantum Dot Solar Cell", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 7, Vol. 3, No. 2, pp. 106-109, June 2011.
- [13] M. Sojoudi, R. Madatov, T. Sojoudi, "Optimization of Efficiency of Solar Cells by Accelerated Electron ray to Have an Optimal and Constant Energy", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 9, Vol. 3, No. 4, pp. 68-71, December 2011.
- [14] S. Nema, R.K. Nema, G. Agnihotri, "Matlab/Simulink Based Study of Photovoltaic Cells/Modules/Array and their Experimental Verification", International Journal of Energy and Environment, Vol. 1, Issue 3, pp. 487-500, 2010.

### **BIOGRAPHIES**



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