MODELING AND SIMULATION OF PHOTOVOLTAIC ARRAYS

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REZUMAT. Această lucrare prezintă o metodă de modelare şi simulare a matricelor fotovoltaice în MATLAB® /Simulink® folosind blocul celula solară din biblioteca SimElectronics®. Metoda este folosită pentru a determina caracteristica unui panou fotovoltaic şi pentru a studia influenţa diferitelor valori ale radiaţiei solare şi ale temperaturii asupra performanţelor celulelor fotovoltaice. Acest model poate fi folosit pentru a construi un model de circuit pentru orice matrice fotovoltaică. Toate modulele care formează modelul sistemului fotovoltaic sunt modelate individual şi validate în Simulink®.

Cuvinte cheie: modelare, celula solară, matrice fotovoltaică, simulare.

ABSTRACT. This paper presents a method of modeling and simulation of photovoltaic arrays in MATLAB® /Simulink® using solar cell block from SimElectronics® library. The method is used to determine the characteristic of a particular photovoltaic cell panel and to study the influence of different values of solar radiation at different temperatures concerning performance of photovoltaic cells. This model it can be used for build a photovoltaic circuit model for any photovoltaic array. All modules which form the photovoltaic system model are individually modeled and validated in Simulink®.

Keywords: modeling, solar cell, photovoltaic array, simulation.

1. INTRODUCTION

Among of the systems which use renewable energy sources, photovoltaic cells are promising, because of the intrinsic qualities of the system itself: very low exploitation costs (free fuel), limited maintenance requirements, reliable, silent and easy to install. In addition, in some stand-alone applications photovoltaic cells are certainly convenient in comparison with other energy sources, especially in those places that are not accessible, which is unprofitable to install traditional power lines [1].

When a new project have to be developed, the requirements and the specifications of the photovoltaic panel are usually unclear, incomplete and not integrated in design process. These are distributed to multiple groups of organizations formed by people with different specializations, which using different tools, and because they work separately, there is no way to test these systems and should be done the step to the integration of already built prototype. When errors are detected in this point is already too late, and usually will have to go back, and its testing can be very expensive [2].

2. SIMULINK® MODEL OF SOLAR CELL

Usually the solar cells are modeled using a specific type of equivalent circuit. Any photovoltaic model is based on diode behavior, which gives to photovoltaic cell its exponential characteristic.

In Simulink® the solar cell can be modeled with three modeling systems [2]. The first possibility of modeling can be done with instruments which can implement any differential equation or algebraic relationship of a highly complex mathematical model. Another possibility is given by Simscape™, which allows direct modeling using physical components of the electric field (resistors, capacitors, diodes) to implement exactly the same mathematical equation.

A modeling system more complex than those described above is performed using SimElectronics® advanced component library, which contains a block called Solar Cell. The solar cell from MATLAB® 7.13 (2011b) is a solar current source, which includes solar-induced current and temperature dependence [3].

A. Solar-induced current. Solar cell block is formed from a single solar cell as a resistance R_s connected in series with a parallel combination of a current source, two exponential diodes and a parallel resistor R_p [3],[4].

The output current I is given by equation (1):

$$I = I_{ph} - I_s \cdot \left(e^{\frac{V+I\cdot R_s}{N\cdot V_t}} - 1 \right) - I_{s2} \cdot \left(e^{\frac{V+I\cdot R_s}{N_2\cdot V_t}} - 1 \right) - \frac{V + I \cdot R_s}{R_p} \quad (1)$$

where I_{ph} is solar-induced current: $I_{ph} = I_{ph0} \cdot I_r / I_{r0}$, where I_r is irradiance in W/m^2 which fall on the cell surface; I_{ph0} is measured solar generated current for the irradiance I_{r0}; I_s is the saturation current of the first diode; I_{s2} is the saturation current of the second diode; $V_t = kT/q$ is the thermal voltage, depend on temperature of the device T, k is the Boltzmann constant and q is the elementary charge of the electron; N is the quality factor (the emission coefficient for the diode) of the first diode; N_2 is the quality factor (the emission coefficient for the diode) of the second diode; V is the voltage at the terminals of the solar cell.

This block allows choosing one of two models: a model with 8 parameters in which the previous equation describes the output current, and a model with 5 parameters if for this equation is applied the following simplifying assumptions: the impedance of the parallel resistor is infinite and the saturation current of the second diode is zero. The model with 5 parameters allows optimization of this block according to the equivalent circuit model parameters or by short circuit current and open circuit voltage [3].

B. Temperature dependence. Several solar cell parameters (the solar-induced current I_{ph}, the saturation current of the first diode I_s, the saturation current of the second diode I_{s2}, the series resistance R_s and the parallel resistance R_p) depend on temperature. Photovoltaic cell temperature is specified by value of the fixed circuit temperature parameter, TFIXED [3].

Between the solar-induced current I_{ph} and temperature of solar cell T [3-5] appears the relation 2:

$$I_{ph}(t) = I_{ph} \cdot (1 + TIPH1 \cdot (T - T_{meas})) \qquad (2)$$

where: $TIPH1$ is the first temperature coefficient for I_{ph}; T_{meas} is the parameter extraction temperature.

3. MODEL OF PHOTOVOLTAIC ARRAY

A. Model for plotting the characteristics of PV module. The model shown in Figure 1 represents a PV cell array connected to a variable resistor. This resistor has an input ramp which just varies resistance linearly in closed circuit until it reaches the 30th steps. Inside the array subsystem are 6 rows of photovoltaic solar cells connected in series, formed by 6 solar cells of SimElectronics® library (Figure 2). This structure can be built in any configurations by connecting multiple strings of solar cells in series or in parallel [2].

Control of solar radiation is realized by Signal Builder block.

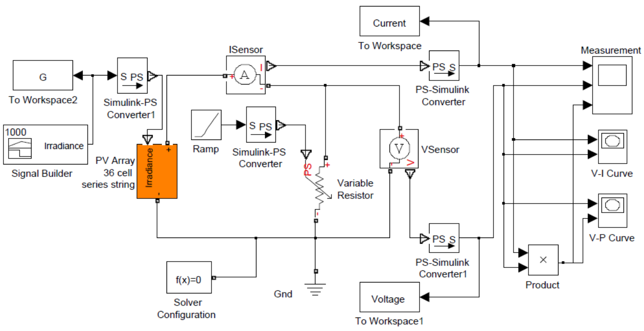

Fig. 1. The Simulink® model for photovoltaic arrays.

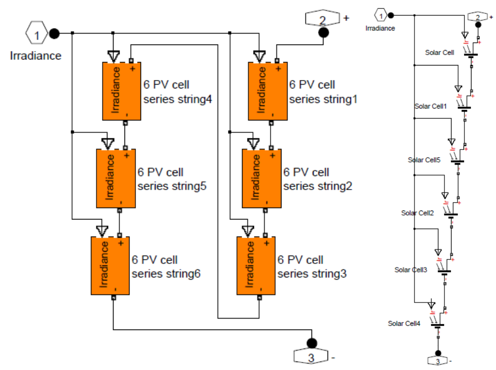

Fig. 2. Connection of solar cells in PV panel subsystem.

The advantage of using of this high level of implementation is to create a simple equivalent circuit, which have much more complex parameters, including the effect of temperature in the device which is very important for behavior of this type of system.

The photovoltaic panel model is validated by simulating at a value of irradiance of $1000\,W/m^2$ and a temperature of $25°C$.

Table 1

The parameters of a single solar cell

Parameter	Value
Short-circuit current [A]	$I_{sc} = 7.34$
Open-circuit voltage [V]	$V_{oc} = 0.6$
Quality factor	N = 1.5
Series resistance [Ω]	$R_s = 0$
First order temperature coefficient for I_{ph} [1/K]	TIPH1 = 0
Temperature exponent for I_s	TXIS1 = 3
Temperature exponent for R_s	TRS1 = 0
Parameter extraction temperature [°C]	$T_{meas} = 25$
Fixed circuit temperature [°C]	TFIXED = 25

In Figure 3 are shown the current, voltage and power which are obtained at output of PV array. These are the curves of current, voltage and power versus time. When the resistance varies, the current and voltage vary depending on the voltage-time relationship which gives the power curve.

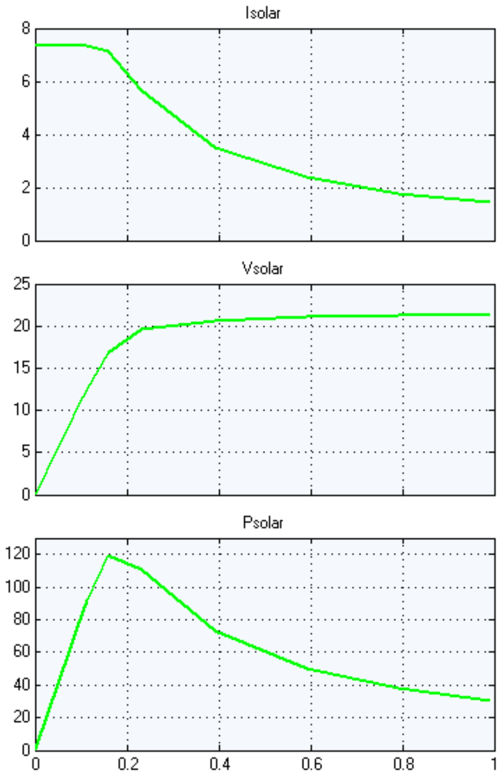

Fig. 3. Current, voltage and power curves for PV array.

The V-I and V-P characteristics of the photovoltaic array is given in Figure 4 and Figure 5. The V-I curve represent the standard behavior of the photovoltaic cell and photovoltaic array respectively. In the middle of this characteristic is the maximum power point. This point is very critical for this kind of system for maximum power extraction from the photovoltaic array. Result that the main objective is to try operating around of this maximum point in order to make the photovoltaic cells to work at maximum efficiency.

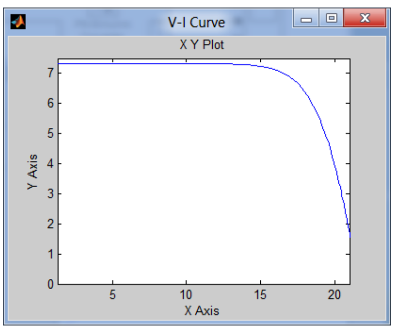

Fig. 4. The V-I characteristics of photovoltaic array.

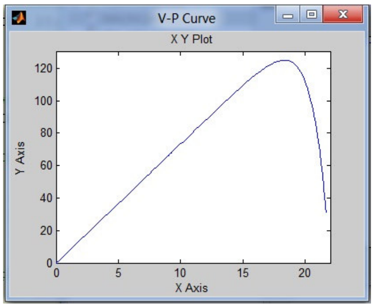

Fig. 5. The V-P characteristics of the photovoltaic array.

B. Modeling using experimental data. Because environmental conditions in which test solar cells are variable, being very hard to have the same level of solar radiation and temperature, is a need for substantial input for the test system [6].

If experimental data and mathematical model are available, MATLAB® and Simulink® provide a very good way to import data from control of these tools or can bring information from Excel into almost any format. In this case, the information can be entered in MATLAB® with tools that allow us to do curve fitting in these data points and can create a three-dimensional surface. MATLAB® allows the capability to do directly mathematical representation to create a Simulink® block which represents the model directly. This principle is shown in Figure 6 [2].

MATLAB® script achieved implement a fixed predictive model based on the characteristic of photovoltaic panel used. This MATLAB® script use Curve Fitting Tool to create a three-dimensional surface for these data points. This surface is then used to generate the current array and the voltage and irradiance vectors necessary to configure the 2D Lookup Table block in Simulink®.

Curve Fitting Tools allows very fast creation of mathematical curves for each of these curves V-I. This tool is a powerful algorithm that allows the realization of polynomial interpolation, or can run a particular equation, which in this case is very close to the one that is accomplished, because it is known the exponential form of V-I curves. This allows access to a plot, in which are five experimental V-I curves corresponding to experimental data obtained at a temperature of $25°C$ for different values of solar radiation [7] (400, 600, 800, 1000 and 1200 W/m^2), from which is loading data to create a photovoltaic array simulator. All the 5 vectors which correspond to the V-I curves are introduced (data can be entered directly or can be imported from Excel), which represents the experimental behavior of the photovoltaic panel [8]. In this example was performed a cubic interpolation. The three-dimensional model of the V-I curves is changed according to solar radiation.

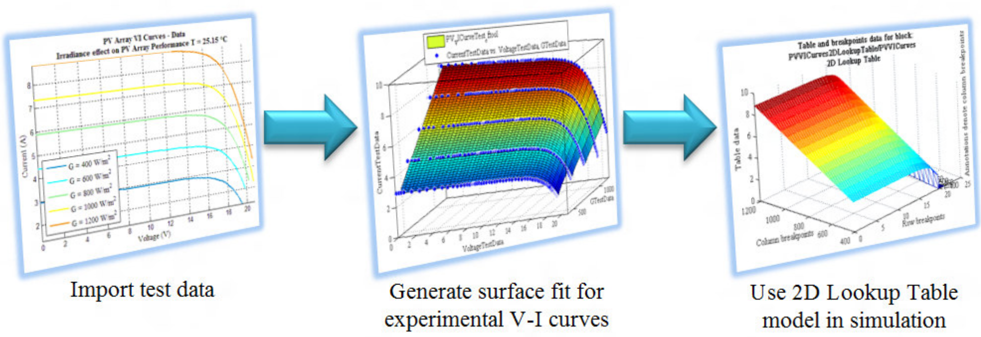

Fig. 6. Model using test equipment data.

In Figure 7 is given the cubic interpolation chart for all 5 V-I curves imported. Using that cubic interpolation algorithm to generate a mathematical equation whose surface represents all points on the V-I curves and all points between them. This interface has several options for saving the graph obtained and also has the option to generate a MATLAB® File, which generates a function called MycreateSurfaceFit, in which are commands and functions for creating mathematical interpolation. The CF Tool can also be opened from the start menu or by typing cftool at the command prompt.

A mathematical representation of the PV-VI surface is realized. In MATLAB® workspace is created a Surface Fit Object. This object contains a mathematical interpolation which provides the current, voltage and the irradiance in this particular case.

The next step is to create an irradiance vector and a voltage vector. Using these vectors on this object surface is calculated what value of current is necessary for the photovoltaic panel.

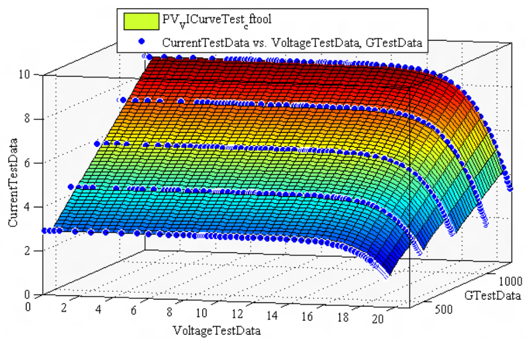

Fig. 7. The three-dimensional model of the V-I curves.

After it is calculated all of these values is created and opened a new Simulink® model using the functionality of MATLAB® to control Simulink® by bringing a 2D Lookup Table block and automatic populating that block with array voltage values, irradiance values and the table data of array current that is calculate from the surface fit.

The model of photovoltaic array (PVVICurves 2D Lookup Table) is with two inputs: the irradiance and the voltage and one output which represent the current. This block, presented in Figure 8, can be used very quickly as a source for a solar array.

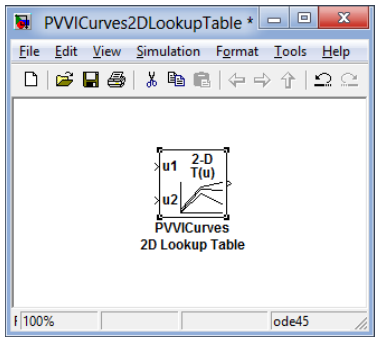

Fig. 8. 2D Lookup Table with PV-VI curves of photovoltaic array.

In this model Curve Fitting Toolbox is used to create a stable fit, because the V-I behavior is static, but the experimental data are for dynamic systems.

The model is validated in Simulink® by simulation according to block diagram shown in Figure 9. Photovoltaic panel, whose scheme is given in Figure 10, is modeled as constant DC source using Photovoltaic V-I Curves 2D Lookup Table block created previously. This block has two inputs: the irradiation input coming from port 1 and have a voltage input, which is like a feedback from the system and in the output of the block is calculated the current. So this model generates a current and receives voltage back from the system.

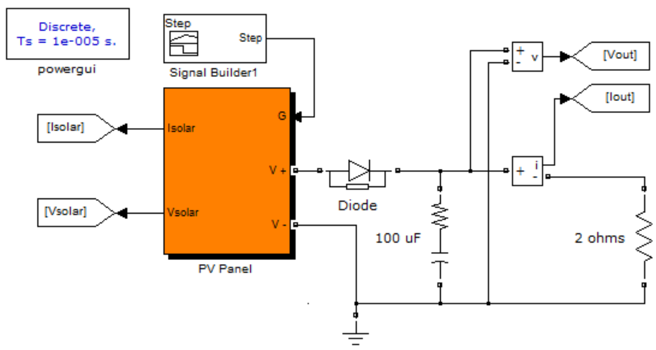

Fig. 9. Simulation of photovoltaic panel.

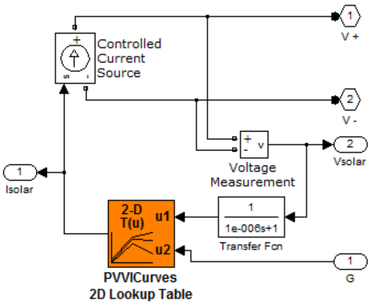

Fig. 10. Solar panel V-I source.

4. EXPERIMANTAL RESULTS

The characteristic V-I curve for radiation incident on the photovoltaic cells is amended as shown in Figure 12 [10]. If the irradiance decreases, the photovoltaic current generated decreases proportionally to that, and variation of no-load voltage is very small [1].

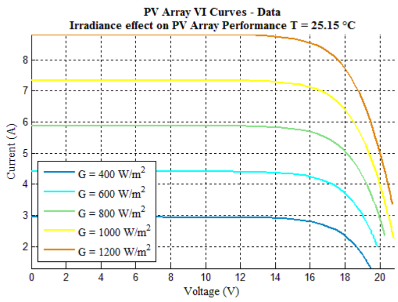

Fig. 12. V-I characteristics for different values of solar radiation at temperature of 25°C.

As shown in Figure 13, when the temperature of module increases the voltage decreases and the produced current remains practically constant. In terms of produced electric power is a reduction in the performance of the photovoltaic panels [1].

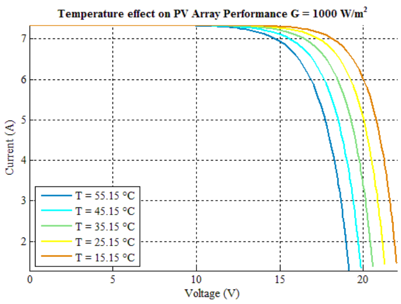

Fig. 13. V-I characteristics for different temperatures.

In Figure 14 are represented the V-P characteristics of the photovoltaic panel for a level of irradiation of 1000 W/m^2 and for different temperatures and, respectively in Figure 15 are given the V-P characteristics for different levels of solar radiation at the temperature of $25°C$ for the photovoltaic panel model shown in Figure 1.

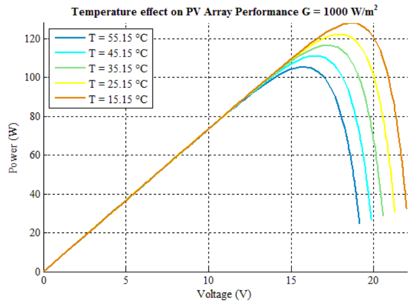

Fig. 14. V-P characteristics for different temperatures.

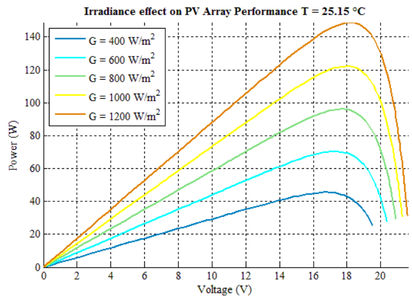

Fig. 15. V-P characteristics for different levels of solar radiation at the same temperature.

In Figure 16 are plotted different levels of irradiation, generated by Signal Builder block. The irradiance data can be imported to Signal Builder from different types of files (excel files, text files or Mat - files) or manually creating a signal. This can allow that real irradiance data to be loaded in the Simulink® model and then entered in the photovoltaic panel. This form of irradiance is used for simulation of the model, the instantaneous change of irradiance not being real. For example this is equivalent to very fast clouds moving, resulting in instant change of sunlight, which cannot happen.

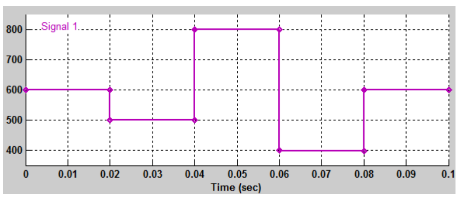

Fig. 16. Variation of solar radiation.

Figure 17 presents the results of the simulation model PV panel shown in Figure 9. The voltage, current and power output of PV panel are represented by green curve and at the output of circuit connected to the photovoltaic panel, they are represented by magenta curve. Irradiance is variable, passing successively through the following values: 600, 500, 800, 400 and $600\,W/m^2$.

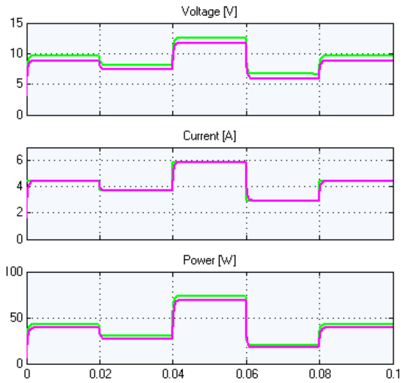

Fig. 17. Voltage, current and power output of photovoltaic panel.

From Figure 15 is observed that for an irradiance of 600 W/m^2 which corresponds to cyan curve, is obtained a maximum power of 70 W and for an irradiation of 800 W/m^2 which corresponds to the green curve, the photovoltaic panel can provide a maximum power of 96 W. That gives an idea of measure in that the power produced by a photovoltaic array is affected by changing of irradiance.

5. CONCLUSIONS

This paper analyzed the implementation of a method for modeling in MATLAB®/Simulink® of photovoltaic arrays and modeling using experimental data. To build photovoltaic panel was used the Solar Cell block, and to implement the fixed predictive model for use as a source for a photovoltaic system was used Curve Fitting Tools to create a three-dimensional surface of the V-I characteristic for the photovoltaic array. The implemented model was validated through simulation.

The simulation results show that the proposed method is efficient in terms of modeling of the functioning of the photovoltaic system.

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