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Application of Bond Graph Modeling for Photovoltaic Module Simulation

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Abstract. In this paper, photovoltaic generator is represented using the bond-graph methodology. Starting from the equivalent circuit the bond graph and the block diagram of the photovoltaic generator have been derived. Upon applying bond graph elements and rules a mathematical model of the photovoltaic generator is obtained. Simulation results of this obtained model using real recorded data (irradiation and temperature) at the Renewable Energies Development Centre in Bouzaréah – Algeria are obtained using MATLAB/SMULINK software. The results have compared with datasheet of the photovoltaic generator for validation purposes.

1 Introduction

The The first law of thermodynamics states that energy cannot be created nor destroyed but simply transformed from one form to another [1], [2]. By modeling the flow of energy from one form to another, a methodology that describes systems in multiple energy domains is obtained. One such methodology is *bond graph* modeling.

Bond graph modeling is one of the powerful tools used for the systemic modeling since it considers the same generic elements for every physical domain [3], [4], [5], and [6]. Where, any dynamic systems can be modeled using the store energy elements (C or I elements) addition to dissipate energy elements (R element) with convert energy elements (transformers and gyrators elements) in addition to the elements that are used to represent external inputs such as source elements (either effort source or flow source) and common effort or common flow relations (that are 0 and 1 junction, respectively). In addition, the dependency between these different elements is recognized by the causal analysis. These elements with the causality provide many advantages to this technique. They make easy the modeling of multi-domain systems such as electrical systems, electromechanical systems, mechanical systems… [5]. Bond graph technique is an energetic representation based on the flow and the effort elements and it offers a compartmental analysis and syntheses using the causality propriety [4].

Photovoltaic generator is a source of finite energy with a non-linear current-voltage characteristic that is directly converts the solar radiation into electricity with no noise and no high temperatures and no pollution. The photovoltaic energy is renewable and inexhaustible, so that, it is more and more intensively used as energy sources in various applications. Moreover, the photovoltaic is a very flexible energy source, its power ranging from microwatts to megawatts. In addition, the photovoltaic modules have a very long lifetime [7], [8] and [9]. In the literature there exist several mathematical models that describe the functioning and the behavior of the photovoltaic generator under different weather conditions (irradiation and temperature) [8], [10], [11] and [12]. These models differentiate from each other by the procedure of the calculation, the accuracy and the number of participant parameters in the calculation of the current-voltage characteristic [8], [10]. The basic element of photovoltaic system is a solar cell which could be considered as a sensor of photon energy. Practically solar cells incorporate a PN junction in a semiconductor across which the photo-voltage is developed [7].

In Algeria, There is an installation located on the roof of Renewable Energies Development Centre "CDER" in Bouzaréah, Algiers uses the Isofoton 106Wp-12 photovoltaic module to produce the electricity into the SONELGAZ grid (public company) without storage device. Such central grid-connected PV systems have an installed power up to the MW range. With such central photovoltaic power stations it is possible to feed directly into the medium or high voltage grid [7].

Many studies have been done on the CDER's PV installation among of them: the authors in [13] proposed a comparative analysis between: PVsyst3 software specific to the conception of the photovoltaic systems and the PSpice software specific for the simulation of the electrical circuit. While, the authors in [10] proposed a mathematical model which directly links the operating electric power to the pump's output water flow rate. This model is based on the analysis of the experimental results carried out in the pumping test facility of Renewable Energies Development Centre. The authors in [14] presented a method that permits to determine the optimum size of battery bank and the PV array for autonomous PV-wind hybrid energy system. And in [8] they determined the electric, hydraulic performances and the costs of the systems of pumping available in the Algerian market. However, the modeling and the simulation of operation of the photovoltaic pumping systems were carried out while being based on the experimentation.

Our study is focused on the application of the bond graph methodology to the Isofoton 106Wp-12 PV module. Therefore, in this paper, the bond graph modeling is introduced and highlighted. In addition, an analytical study of photovoltaic generator installed on the Renewable Energies Development Centre in Algeria is investigated using bond graph approach under different weather conditions. The obtained bond graph mathematical model of the PV generator is compared with that obtained using Kirchhoff's law. A comparison between real data and that given in the datasheet is done.

2 Bond graph methodology

Bond graphs actually indicate the structure through which energy is exchanged [5]. It represents the power transfer within a system by using a series of connections called power bonds [1], [15]. It is a graphical language that constitutes an intermediate between the studied physical system and the mathematical formulation (transfer function or matrix, linear or non linear state equation) necessary for its model. With the ability to map the power flow across energy domain boundaries, and map the signal flow information across the same boundaries, is an indispensable aid in the user's quest to form cause and affect relationships within interdisciplinary systems.

The bond graph modeling utilizes nine basic elements or building blocks which may represent physical subsystems, components or phenomena in every energy domains. The elements are classified in three categories, the passive elements and the active elements and the elements of the junction. These elements in addition to the detectors are used to represents the phenomenon that connect the generalized variables. For more details of bond graph methodology see [3], [15], [16], and [17].

3 Photovoltaic generator

The photovoltaic panel results to the combining of photovoltaic cells in series or in parallel or in both series and parallel. Basically, photovoltaic cell is a P-N semiconductor junction that directly converts light energy into electricity. Figure 1 represents an equivalent electrical circuit of a single solar cell and its bond graph.

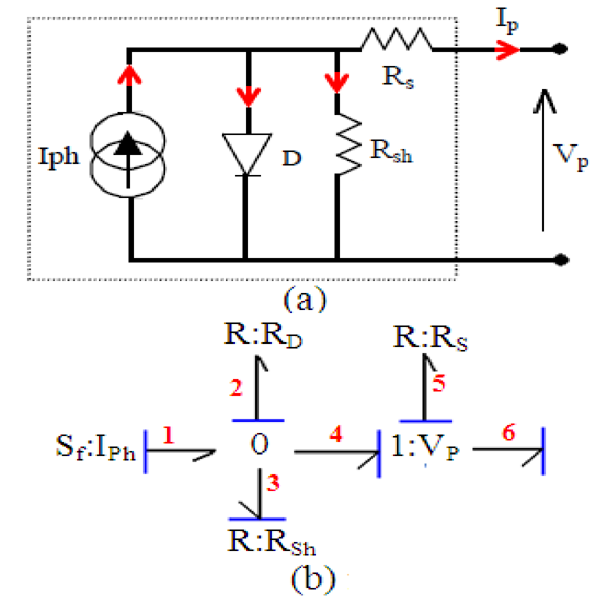

Fig. 1. (a) Equivalent electrical circuit and (b) its bond graph model of the photovoltaic cell.

This equivalent electrical circuit consists of a current source I_{ph} which depends on the solar radiation and on the temperature, a diode D on parallel in which the intensity of inverse saturation depends on the temperature, and the series resistance Rs which represents the material resistivity as well as the ohmic losses due to levels of contact. The shunt resistance R_{Sh} represents the cell leakage.

The bond graph representation of the photocurrent source (Iph) is a source flow Sf, while the shunt and series resistances both are represented by a resistance R_S and R_{Sh}, respectively. The diode (D) is represented by a resistance R_D, as shown in Fig. 1, (a). Using the assignments rules of the causality on the junction elements (0 and 1), the output of the block diagrame is the cell output voltage V_{Cell} that is represented by e_6 and given by (1). Using this equation, the obtained cell current given by (2) is similar to that used in [9], [11], [13], [14], [18], [19], [20], [21] and [22].

$$e_6 = V_{Th} \ln\left(\frac{I_{Ph} - \frac{R_S}{R_{Sh}} I_{cell} - \frac{1}{R_{Sh}} V_{cell} - I_{cell}}{I_{Sat}} + 1 \right) - R_S I_{cell} \quad (1)$$

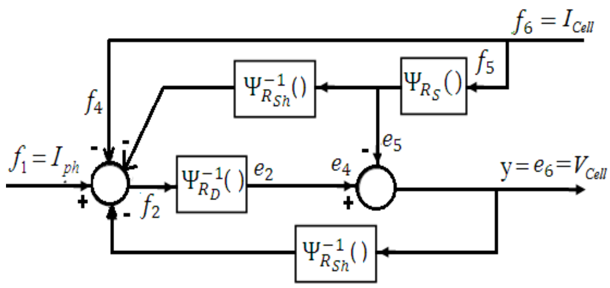

Fig. 2. The block diagram of Fig. 1.

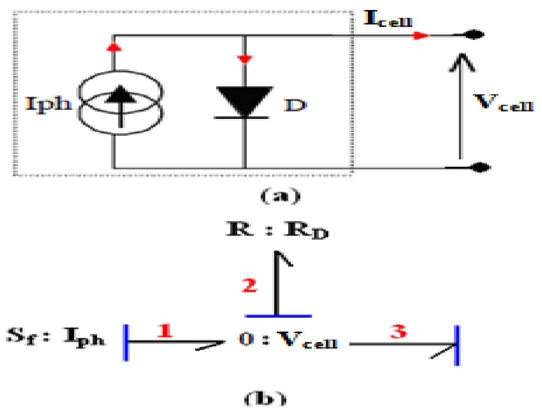

Fig. 3. (a) Equivalent electrical circuit and (b) its bond graph model of photovoltaic cell.

$$f_6 = I_{ph} - I_{sat}\left(\exp^{\frac{V_{cell}+R_S I_{cell}}{V_{Th}}} - 1\right) - \frac{V_{cell}+R_s I_{cell}}{R_{sh}} \quad (2)$$

with I_{ph} is the photo-current that is equal to the short-circuit current I_{SC}, I_{sat} is the reverse saturation current of the diode, V_{Th} is the thermal voltage.

Since the shunt resistance R_{sh} is very large and the serial resistance Rs is very small they can be removed from the circuit shown in Fig. 1 yields a simplified equivalent circuit as shown in Fig. 3 and its block diagram is shown in Fig. 4.

The output of the block diagrame of the bond graph model is the cell output voltage V_{Cell} that is represented by e_6. Using the characteristic equation of the junctions with the consideration of the causality results the cell output voltage V_{Cell}, represented by e_3, and the cell current I_{Cell} , represented by f_3, which are given by (3) and (4), respectively.

$$e_3 = V_{Th} \ln\left(\frac{I_{Ph} - I_{cell}}{I_{Sat}} + 1\right) \quad (3)$$

$$f_3 = I_{ph} - I_{sat}\left(e^{\frac{V_{cell}}{V_{Th}}} - 1\right) \quad (4)$$

This equation is used in [23] and [24].

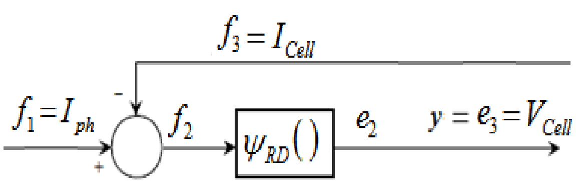

Fig. 4. Block diagram of the bond graph model of Fig. 3.

The two key parameters often used to characterize a photovoltaic cell are the short-circuit current and the open-circuit voltage which are provided by the manufacturer's data sheet [23]. Equation (4) indicates that the cell can be described by the relation linking the photo-current of cell to the reverse saturation current of the diode with the cell voltage. Figure 5 shows the output power and the V-I characteristics of the photovoltaic cell as a function of its voltage for Isofoton 106Wp-12 photovoltaic module at standard conditions.

For any connection of the cells the resulting mathematical model of the PV generator is given by (5 and 6). With V_{ThG} is the generator thermal voltage, I_{phG} is the generator PV current and I_{satG} is the generator saturation current.

$$I_{PVG} = I_{phG} - I_{satG}\left(e^{\frac{V_{PG}}{V_{ThG}}} - 1\right) \quad (5)$$

$$V_{PVG} = (V_{Th} N_S)\ln\left(\frac{N_p I_{ph} - I_{PVG} + N_p I_{sat}}{N_p I_{sat}}\right) \quad (6)$$

This equation is used in [21] and [25]. The output power of the of the photovoltaic generator is given by the following equation

$$P_{PVG} = I_{PVG} V_{PVG} \quad (7)$$

Consider the Isofoton 106Wp-12 photovoltaic module consisting of thirty six cells in series with two cells in parallel. Therefore, the total module output voltage is increased by 36 times the output voltage of a single cell while the module output current is the double of the single cell current.

Figure 6 shows the non-linear current-voltage characteristic of the photovoltaic panel under the standard climatic conditions.

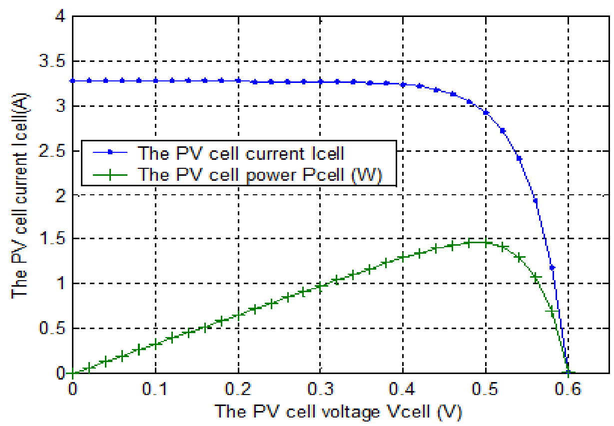

Fig.5. The V-I characteristics and the output power of photovoltaic cell as a function of its voltage V_{cell}.

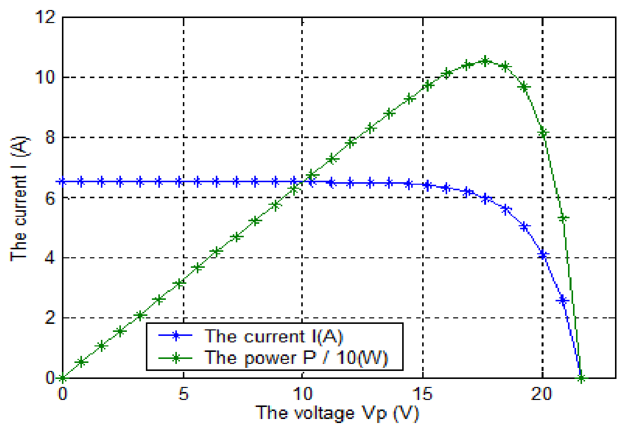

Fig. 6. The V-I characteristics and the output power of photovoltaic module as a function of its voltage Vcell.

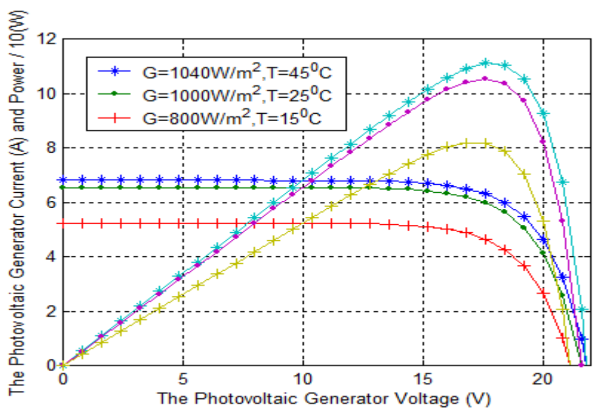

Fig.7. The I-V characteristic and the output power of the photovoltaic panel as a function of its voltage V_p.

A comparison between the Isofoton 106Wp-12 photovoltaic module parameters given in the data sheet and the results obtained using the previous equations with MATLAB software and real data, is given in table 1. This table shows that the obtained maximum output power of this PV module is 0.6234w less than the nominal power of Isofoton106Wp-12 PV module.

In other word, the obtained maximum output power of this PV module is 99.412% of its nominal output power which is given in the datasheet under the standard climatic conditions. Where, the corresponding PV module voltage is higher by 0.1950 V while the corresponding PV module current is lower by 0.1110A than that are mentioned in the data sheet.

Table 1. Comparison Between data sheet and the real data

	ISOFOTON 106Wv-12		
	Data sheet	simulation	Error
Maxim Power Pmax (W)	106	105.3762	0.6238
I_M at Pmax (A)	6,1	5.9845	0.1155
V_M at Pmax (V)	17,4	17.6083	0.2083

For different values of temperature and irradiation the non-linear current-voltage characteristic of the photovoltaic panel is shown in Fig.7. Where, as the irradiation and the temperature are higher the resulting output power of the photovoltaic panel is higher, but the nominal power of the photovoltaic panel is obtained under the standard climatic conditions.

4 Photovoltaic array

The photovoltaic array results to the combining of panels in series and/or parallel arrangements [6]. For practical application, considering the installation located on the roof of the Renewable Energies Development Centre in Bouzaréah-Algeria.

In this installation the Isofoton 106Wp-12 photovoltaic module is used to produce the electricity into the SONELGAZ grid without storage device. This photovoltaic station that has a nominal power of 9.54 KW is composed of three sub-arrays. Where, each sub-array is consisting of two parallel strings of fifteen modules (Isofoton 106Wp-12) connected in series with nominal power equal to 3.18 KW.

Figure 8 shows the I-V characteristic and the output power of the photovoltaic sub-array as a function of its voltage. Where, the total sub-array output voltage is increased by fifteen times the output voltage of the single PV module while the sub-array output current is the double of the single PV module output current. The obtained maximum power of this PV sub-array is 18.7013W less than its nominal output power. In other word, the obtained maximum power of this PV sub-array is 99.412% of nominal power of this PV sub-array under the standard climatic conditions.

Note that those percentages are similar to that obtained for the PV module. By multiplying the maximum output power of this sub-array by the number of the sub-arrays used in this installation the total output power of this installation is obtained equal to 9.4839KW which is less than its nominal output power by 56.1W.

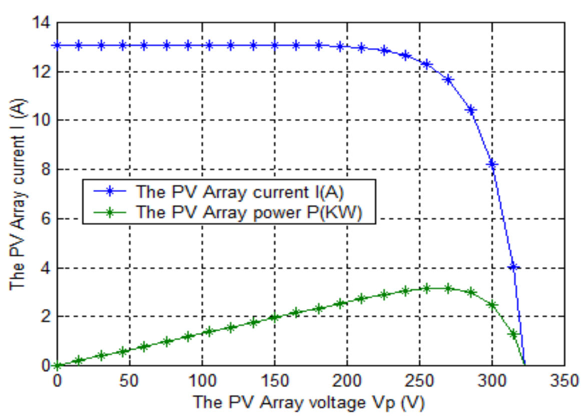

Fig.8. I-V characteristic and the output power of the photovoltaic array as a function of its voltage.

In other word, under the standard climatic conditions the obtained maximum out power of this PV array is 99.412% of its nominal output power. In addition, it is necessary to track the maximum power point all the time.

Where, several researches have been focused on the various Maximum Power Point tracking to lead the operating point of the photovoltaic generator to optimum point. Among of them: the constant voltage method, the perturbation and observation method and incremental conductance method [18], [25].

5 Conclusion

In this paper, bond graph approach has been applied to model photovoltaic generator. A real photovoltaic which is installed at the Renewable Energies Development Centre in Bouzaréah, Algiers and connected to the grid utility (SONELGAZ) has been the subject of the power modeling. Comparison of the obtained results with those mentioned in the datasheet of the photovoltaic generator has result to be in accuracy of 99.412%. Such modeling accuracy confirms the powerfulness of bond graph as a tool of modeling.

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