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Modelling Photovoltaic System Using Bond Graph Method: A Comparative Study

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Abstract: *Bond Graphs (BG)are perceived as a promising possibility for modeling complex physical systems. This paper explores its potential by undertaking the analysis, modeling and design of a photovoltaic (PV) solar system. A model of a photovoltaic solar system is performed using Bond Graph Approach based on a 1-diode/2-resistors (1D & 2R) circuit model. The main aim of this model is to study and master the behavior of this PV system. Moreover, it seeks building up a better and more reliable PV model to replicate the exact I-V characteristics. To validate the accuracy of the proposed model, a comparison with MATLAB PV model was carried out. Simulation results of this model were obtained using 20-Sim software. The outcome reveals that the model replicates MATLAB PV model curve to a very good degree of accuracy under the considered operating conditions.*

Keywords: *Bond Graph, Modeling, Matlab Simulink, Photovoltaic System*.

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I. Introduction

Solar energy remains the most promising renewable energy source when it comes to power generation [1,2]. Due to the relative high initial cost of a solar photovoltaic (PV) system - which convert solar energy into electrical energy - an accurate assessment of the electrical characteristics is vital to optimizing the electrical behavior of the PV source itself and the operation of power conversion systems. Photovoltaic generator is a source of finite energy with a non-linear current-voltage characteristic that directly converts the solar radiation into electricity with no noise and no pollution. There are several mathematical models that successfully describe the performance and nonlinear behavior of PV systems. The most common and widely adopted ones are the single diode model and double diode model [3]. The modelling of photovoltaic system elements is an indispensable and important step that must precede any application of sizing, identification or simulation. Different models developed for PV applications were presented in several papers [4,5,6,7,8,9]. The photovoltaic system modelling is complex. That's why we propose the use of Bond Graph (BG) method which enables the decomposition of the system into subsystems exchanging energy, and to represent several physic domains with a unified way.

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 [10,11,12,13]. Each dynamic system 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). The dependency between these different elements is recognized by the causal analysis. These causality elements put many advantages to this technique. They make easy the modeling of multi-domain systems such as electrical, electromechanical, mechanical systems [13]. Bond Graph technique is an energetic representation based on the flow and the effort elements and it offers a behavior analysis and syntheses using the causality propriety [12].

Our study is focused on the application of the Bond Graph Methodfor modeling Photovoltaic system, Its goal is to study and master the behavior of the PV system. An introduction to Bond Graph Approach is reported in Section 2. A detailed bond graph model of photovoltaic generator is proposed in Section 3. The comparative results of this study are given in Section 4. Finally, concluding remarks are presented in Section 5.

II. Fundamental concepts of bond graphs

A Bond Graph [14,15,16,17] is a graphical way of modeling physical systems. All these physical systems have in common the conservation laws for mass and energy. Bond graph, originated by Paynter in 1961, deals with the conservation of energy. This gives a unified approach to modeling physical systems. Further follows a short introduction to this modeling tool, more information can be found in. The bond graph based modelling has several advantages over conventional simulation methods as follows:

1. Providing a visual representation of the design;
2. Controlling the consistency of the topological settings of the design;
3. Providing the hierarchical modelling of designs;
4. Extracting the system equations symbolically in a structured way.

Within physical systems, energy is transported form one item to another. This energy is either stored or converted to other forms. However, the important thing is that it does not dissipate. If the energy is changing in one place, it also changes in an opposite way at another location. The definition of power P is the change in energy E with respect to time:

$$P = \frac{dE}{Dt} \quad 1)$$

This power is transferred between the different parts in bond graph model with the use of power bonds, see Fig. 1. Power can be expressed as the product of an effort and a flow variable, thus the general expression:

$$P = e(t)f(t) \quad (2)$$

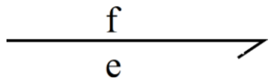

Fig. 1 Power bond with effort and flow

The symbols e(t) and f(t) are used to denote effect and flow quantities as functions of time. Table 1 shows what the effort and flow quantities can be in some familiar domains.

Table 1: Effort and flow variables in different domains

Domain	Effort, e(t)	Flow, f(t)
Mechanical translation	Force, F(t)	Velocity, v(t)
Mechanicalritation	Toque, τ(t)	Angularvelocity, ω(t)
Hydrolic	Pressure, P(t)	Volume flow rate, Q(t)
Electric	Voltage, U(t)	Current, i(t)

2.1. System Elements

In bond graph modeling there are a total amount of nine different elements. We will also here introduce the causality assignments, but first we have to explore the cause and effect for each of the basic bond graph elements.

2.1.1. Junctions:

There are two different types of junctions that connects the different parts in a bond graph model. The 0-junction and the 1-junction. The 0-junction is an effort equalizing connection, see Fig. 2 and its corresponding equations in (3). Since the efforts are the same, only one bond can decide what it is. The 1-junction is a flow equalizing connection, see Fig. 3 and its corresponding equations in (4). Since the flows are the same, only one bond can decide what it is. Which bond decides the flow and which one decides the effort is indicated with the vertical causality stroke. If the vertical line is closest to the junction, then this element decides the effort, furthest away from the junction decides the flow.

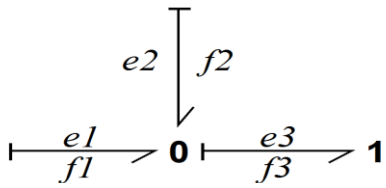

Fig. 2 0-junction

$$\begin{cases} e_1 = e_2 = e_3 \\ f_3 = f_1 + f_2 \end{cases} \quad 3)$$

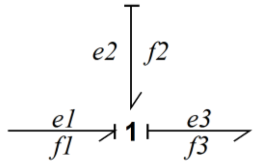

Fig. 3 1-junction

$$\begin{cases} f_1 = f_2 = f_3 \\ e_3 = e_1 + e_2 \end{cases} \quad (4)$$

2.1.2. Source Element

We can divide the source elements into two different kinds, effort- and flow-source. The effort source gives an effort into the system, then it is up to the system to decide the flow. This is what is meant with cause and effect, and its vice versa for the flow source. Fig. 4 shows how the causality is indicated on the graphical elements. For the source elements these causality assignments are fixed.

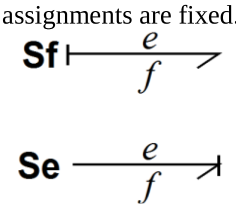

Fig. 4 Effort and flow source with their causality assignment

2.1.3. Compliance Element

The causality assignment for the C-element has two possibilities, but one is preferred in contrast to the other. This is discussed at the end of this section. The preferred case is seen in Fig.5 and its corresponding equation in (5). We see from both the equation and the figure that flow is given to the element/equation and it gives the effort in return.

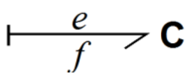

Fig. 5 Example of a compliance element with integral causality

$$e = \frac{1}{C}\int \mathrm{f}dt = \frac{q}{C} \quad 5)$$

The variable *q*is called the generalized displacement. For example, this can be rotational position of the rotor in a wind turbine.

2.1.4. Inertia Element

There are two choices for the causality assignment for the I-element, also here one is preferred in contrast to other. The preferred case is seen in Fig. 6 and its corresponding equation in (6).

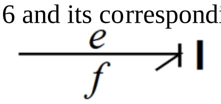

Fig. 6 Example of an inertia element with integral causality

$$f = \frac{1}{I} e = \frac{p}{I} \quad 6)$$

The variable p is called the generalized momentum. For example, this can be rotor inertia times rotor velocity in a wind turbine.

2.1.5. Resistive Element

It is a bit more freedom when it comes to the causality assignment for the R-element. Its equation do not include any dynamics, it is only an algebraic expression. The two causality choices are shown in Fig. 7 and its corresponding equation in (7).

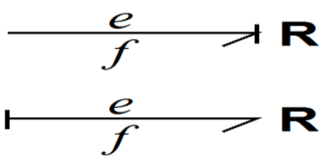

Fig. 7 Example of resistive element

$$f = \frac{e}{R} \quad \text{or} \quad e = Rf \qquad 7)$$

2.1.6. Transformer Element

The transformer element can work in two ways; either it transforms a flow into another flow or it transforms an effort into another effort. Fig. 8 corresponds to (8), where m is the transformation ratio. For example, this can represent a mechanical gearing or an electric transformer.

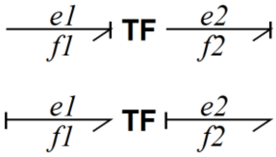

Fig. 8 Example of the two transformers

$$f_1 = \frac{f_2}{m}, \quad e_2 = \frac{e_1}{m} \quad \text{or} \quad f_2 = mf_1, \quad e_1 = me_2 \qquad 8)$$

2.1.7. Gyrator Element

The gyrator can also work in two ways; either it transform a flow into an effort or it transform an effort into a flow. Fig. 9 corresponds to (9), where r is the gyrator ratio.

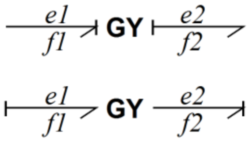

Fig.9 Example of the two gyrators

$$f_1 = \frac{e_2}{r}, \quad f_2 = \frac{e_1}{r} \quad \text{or} \quad e_1 = rf_2, \quad e_2 = rf_1 \qquad 9)$$

By using bond graph as the modeling tool we get a good overview of the models physical structure and we can do simulations in one step, instead of first deriving the equations and then drawing the block diagram.

III. Bond Graph Of PV System

The PV system modelling has been extensively treated especially for parameters identification, sizing, and simulation or optimization objectives [18,19,20,21]. The used models are in majority static and hardly adapted to dynamic variations. To avoid these difficulties, we propose a mathematical representation using Bond Graph approach, which whose efficiency was proved in modelling, simulation and analysis or control law design for different applications [14]. In this work, itis used in order to simulate and to study the behavior of a PV system cell.

The one diode model (Fig. 10) often describes the electric behavior of a PV cell. In this model, an electric current generator represents the photovoltaic generator, which is equivalent to a current source I_{pv} (Equation (12)) - which is function of solar radiation G and temperature cell T - in parallel with a diode with a non-linear current-voltage characteristic that directly converts the solar radiation into electricity. Moreover, in series with resistance R_s that represents the material resistivity as well as the ohmic losses due to levels of contact. The shunt resistance R_p describes the cell leakage. Fig. 10sketches the equivalent electrical circuit of PV cell.

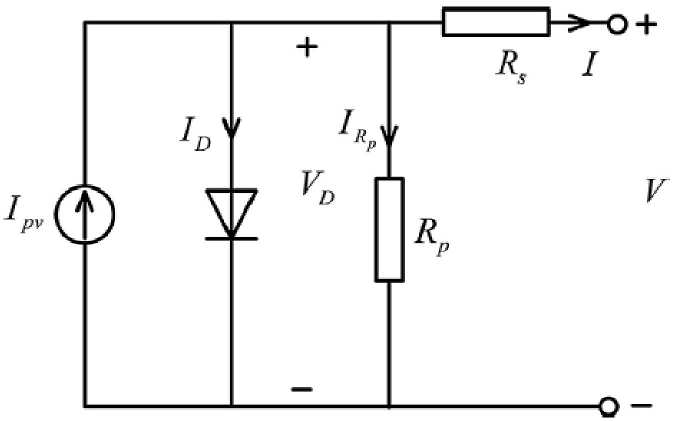

Fig. 10 Equivalent electrical circuit of PV cell

The Bong Graph model of the PV system - which can be directly obtained from the equivalent electrical circuit - is depicted in Fig. 11. The photocurrent source (I_{pv}) is modeled by a modulate flow source *MSf*, because the photocurrent (I_{pv}) depends on the solar irradiance *G* and cell temperature *T* and is given by:

$$I_{pv} = I_{pv,ref}\left(\frac{G}{G_{ref}}\right)[1 + \alpha'_T(T - T_{ref})] \qquad 10)$$

where $I_{pv,ref}$ is the photo current at standard reference conditions, G_{ref} is the reference solar irradiance and T_{red} is the reference cell temperature, α'_T is the relative temperature coefficient of the short-circuit current, which represents the rate of change of the short-circuit current with respect to temperature. Manufacturers occasionally provide the absolute temperature coefficient of the short-circuit current, α_T, for a particular panel. The relationship between α'_T and α_T is

$$\alpha_T = \alpha'_T I_{pv,ref} \qquad 11)$$

The resistance R_s and R_p, are respectively represented by R-elements, the diode (D)by a variable and nonlinear R-element (R_D), whose characteristic is governed by the following equation.

$$I_D = I_0\left(\exp\left(\frac{qV_D}{nkT}\right) - 1\right) \qquad 12)$$

whereI_0 is the diode saturation current or cell reverse saturation, *q*the electronic charge ($q = 1.602.10^{19}$ *C*), *k* the Boltzmann constant ($k = 1.3806503.10^{23}$ *J/K*), *n* the ideality factor or the ideal constant of the diode.

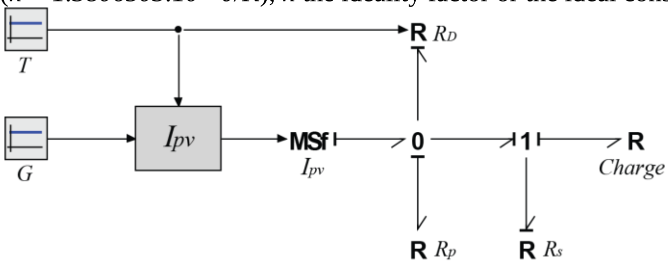

Fig. 11 Bond Graph model of PV cell

The photovoltaic panel model is obtained through the combining of photovoltaic cells in series (to increase the voltage), in parallel (to increase the current), or in both series and parallel using equations 2 and 3.

$$I_{pan} = I_{cell} N_{cell\_p} \qquad (13)$$

$$V_{cell} = V_{pan} / N_{cell\_s} \qquad (14)$$

whereI_{pan} is the current panel, $I_{cell}$the current cell, N_{cell_p} number of cells in series, $V_{cell}$the voltage cell, $V_{pan}$the voltage panel and N_{cell_s}number of cells in parallel.

3.1. PV Array Simulink Block

The PV Array block, realized in Matlab Simulink, implements an array of photovoltaic (PV) modules. The array is built of strings of modules connected in parallel, each string consisting of modules connected in series. This block allows to model preset PV modules from the National Renewable Energy Laboratory (NREL) System Advisor Model (Jan. 2014). Block diagram model of a PV array by Matlab Simulink is presented in Fig. 11.

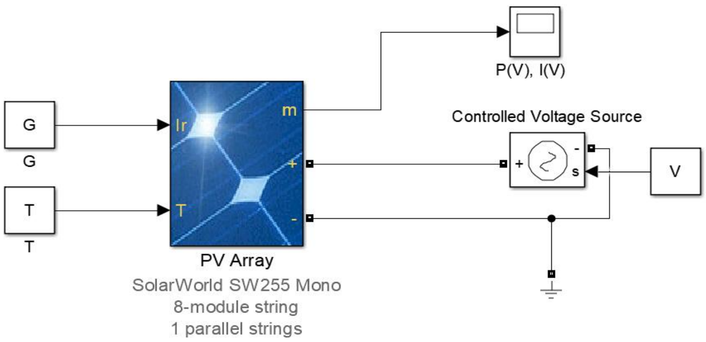

Fig. 12 Matlab SimulinkBlock diagram model of a PV array

IV. Simulation And Results

In order to check out that the MATLAB/Simulink model and the Bond Graph model are the same interpretation, we set the temperature and irradiation to different values and we apply a voltage panel as a ramp function then we simulate the non-linear current-voltage characteristic and power-voltage characteristic of the photovoltaic panel. For our simulation, we consider the SolidWord SW225 Mono photovoltaic module consisting of sixty cells in series. All the relevant parameters are given in the data sheet of this module. Figs. 13and 14 show the simulation results.

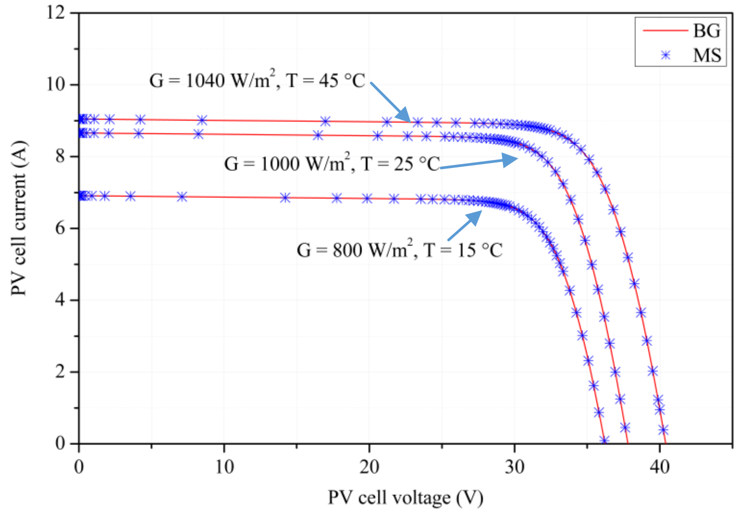

Fig.13 The I-V characteristic of thephotovoltaic panel

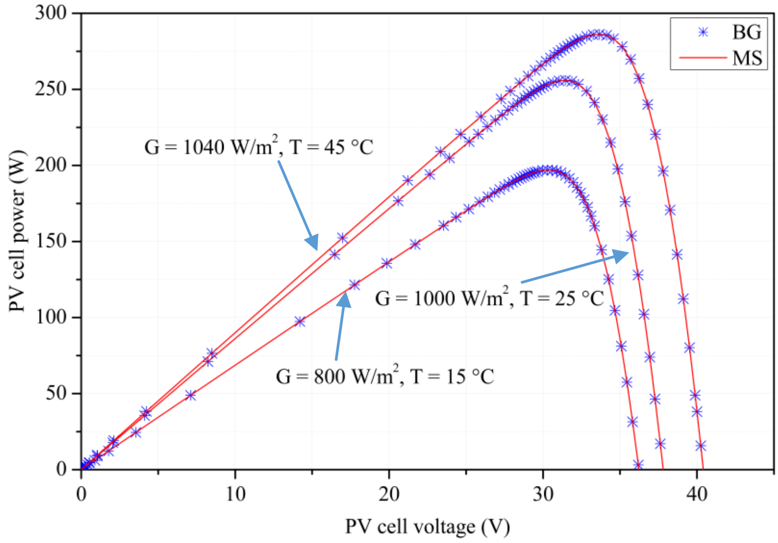

Fig. 14 The output power of thephotovoltaic panel as a function of its voltage

For different values of temperature and irradiation, thenon-linear current-voltage characteristic of thephotovoltaic panel is shown in Fig. 13. For higher levels ofirradiation and the temperature, we get higherphotovoltaic panel current.This figure shows also that both Bond Graph (BG) model and Matlab Simulink (MS) model have exactly the same curve. Fig. 14showsthe outputpower of the photovoltaic as a function of itsvoltage, the powerisincreasedwith the temperature and irradiation. Also the Bond Graph model and Matlab Simulink model curves match perfectly. These simulations confirm the validity of the Bond Graph model.

V. Conclusions

The purpose of this paper was to devlop a Bond Graph model for a photovoltaic system. This has beenachievedthrough a 1-diode/2-resistor (1D & 2R) circuit model. The simulation outcomes are then compared with PV Array Simulink Block made in Matlab Simulink. Simulation results from both models feature a very high degree of coincidence, which confirms one of the many benefits of Bond Graph approach as a generally usable approach to modeling physical systems of arbitrary types.

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