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# Bond Graph Modelling of Different Equivalent Models of Photovoltaic Cell

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**Abstract**

The photovoltaic (PV) generator current-voltage equation is nonlinear and need a powerful algorithm to solve it. In this paper a dynamic modelling approach of photovoltaic generator is presented by the bond graph (BD) methodology. The BD is a graphical methodology for modelling and analysis of physical systems. It's based on decomposition of the system in subsystems and exchange energy. Therefore, using the single and double diode models representation of equivalent circuit of PV generator, the bond graph representation is derived. The mathematical model is obtained by applying the bond graph elements and rules. At the end, the simulation results of these obtained models using experimental points are plotted.



*Keywords:* Photovoltaic generator; Bond graph; Electrical circuit; Mathematical model.

## 1. Introduction

In recent year, modelling of solar cell and PV panel became an important topic of research [1]. The modelling necessarily requires taking the irradiance and temperature as input variables [2] [3]. So, any change in the irradiance

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**Nomenclature**

| | |
|---|---|
| $R_d$, $R_{d1}$, $R_{d2}$ | diode resistance |
| $Vd$ | diode voltage |
| $I_d$, $I_{d1}$, $I_{d2}$ | diode current |
| $I_{ph}$ | photocurrent |
| $I_s$ | saturation current of diode |
| $n$ | quality factor of P-N junction |
| $V_T$ | Thermal voltage |
| $R_{sh}$ | shunt resistance of photovoltaic cell |
| $MSF$ | flow source |
| $C_D$ | diffusion capacitance |
| $PV$ | photovoltaic |
| $BD$ | bond graph |

and temperature immediately implies changes in characteristics current-voltage and power-voltage curves [4]. In this research area, several models have been used to describe the equivalent electrical circuit of a PV cell: the single diode, double diode model and the dynamical model with diode capacitance. The accuracy of solar cell models greatly depends on their model parameters [5]. Several studies in literature are currently focusing on solar cell modelling, thus developing several electric models, with different level of complexity [6]. Generally, the single and double diodes are the most used models for representing the PV cell electrical behavior [7]. However, it is important to model the solar cell with additional approaches and methodologies.

In this paper, a modelling solar cell is presented, by using a dynamical bond graph: this is a graphical methodology for modelling and analysis of physical systems using the decomposition of the system in subsystems and with exchanging energy. The bond graph modelling is one of powerful methodology used in dynamical and complex physic system. Thus, the bond graph is a commonly used methodology for complex system, having in common the conservation laws for mass and energy. It is based on the fact that energy can’t be created or destroyed but transformed from one form to another. The bond graph theory is already applied in several areas such as; mechanics [8], hydraulics [9], electricity [10], nuclear reactor [11], complex energy systems [12]. The bond graph methodology has been used also in PV systems; control and optimization of the maximum power point, parameters extraction [13] and electro-thermal solar cell modelling [14]: in these papers the series resistance has been considered zero and the shunt resistance infinity.

The innovative interest of the proposed research is in the use of bond graph as a multidisciplinary tool for dynamic modelling of a different electrical equivalent circuit of solar cell such as; single diode, double model and diode capacitance model. Furthermore, the governing equations of mathematical model for single and double diode model are determined from graphical modelling, to simulate the current-voltage and power-voltage under different values of temperature and irradiance. To validate the proposed method: the results of the simulation of these models obtained using experimental points will be reported.

## 2. Bond Graph model of photovoltaic cell

The bond graph methodology is a suitable modelling of photovoltaic cell cause of its nonlinearity and complexity [15][1]. The modelling approach permits the decomposition of the system into subsystems exchange energy. In this modelling, we are interested to present the bond graph modelling of electrical behavior of photovoltaic cell in three models. The single diode model is presented by an electric current source in parallel with diode and parasitic series and shunt resistances. The shunt resistance and the resistance of diode introduce uncertainty in the causal structure. If we give a conductive causality to shunt resistance, the diode resistance has causality. This introduces an algebraic loop between the shunt resistance and diode resistance as the flow in shunt resistance depends on the effort given by diode resistance. The diode resistance is defined with the implicit expression as follows:

$$R_d = V_d / I_d \tag{1}$$

$$I_d = I_s\left(\exp(V_d/nV_T)-1\right) \quad (2)$$

$$V_d = \left(I_{ph} - I_d - I\right)R_{sh} \quad (3)$$

The equivalent bond graph of photovoltaic is modelled by flow source $MSF=I_{ph}$, change with incident solar irradiation and the temperature. The diode is represented by modulated nonlinear resistance and its current-voltage characteristic depends on ambient temperature. In the following figure we present the electrical equivalent circuit of each model with bond graph representation.

For single diode model

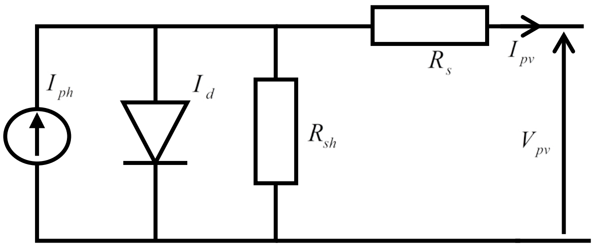


Fig. 1. equivalent circuit of photovoltaic cell single diode

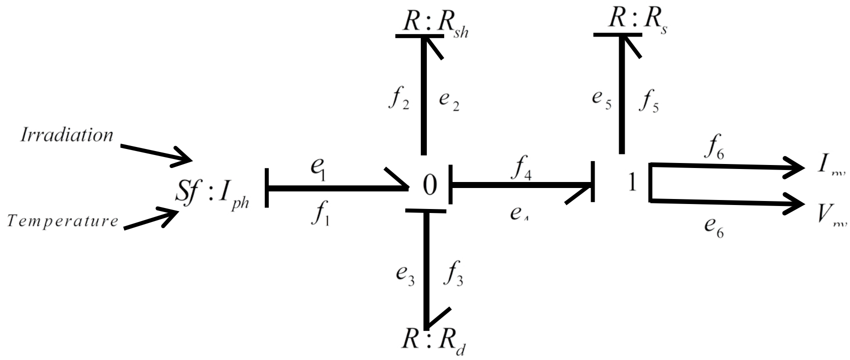


Fig. 2. bond graph representations of photovoltaic cell single diode.

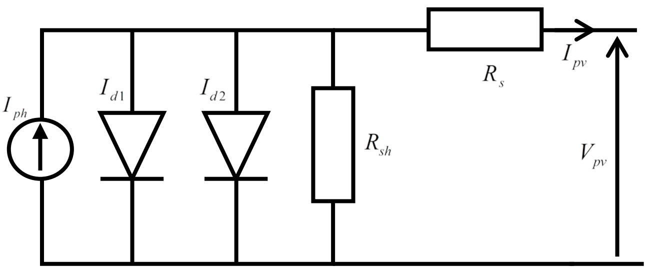


Fig. 3. equivalent circuit of photovoltaic cell double diode

For double diode model the equivalent electrical circuit and bond graph representations are presented in Fig.3 and 4, respectively. Moreover, the capacitance model, the Fig. 5 presents the dynamical equivalent circuit, while the Fig. 6 presents the bon graph presentation.

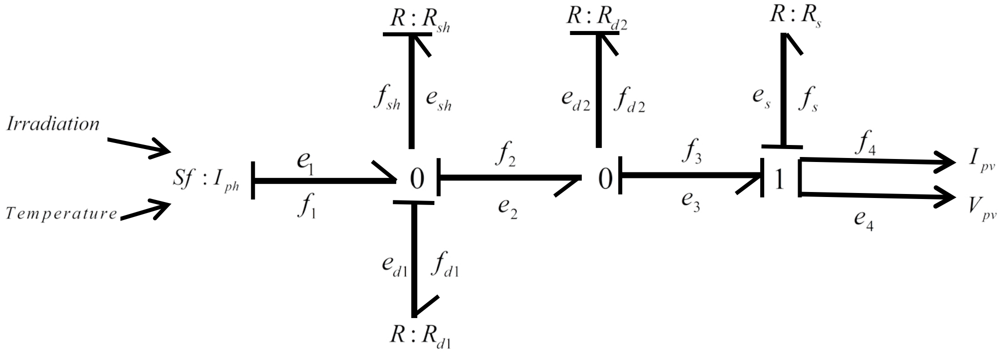


Fig. 4. bond graph representations of photovoltaic cell double diode model.

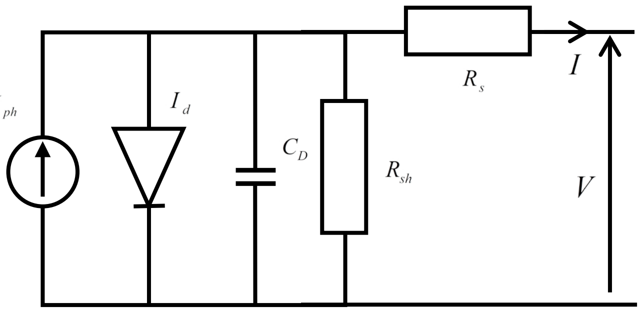


Fig. 5. photovoltaic representation with diode capacitance

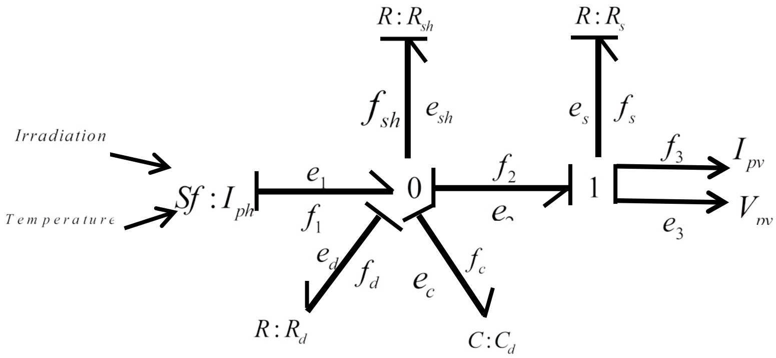


Fig. 6. bond graph representations with diode capacitance.

## 3. Generation of the equations

The electrical photovoltaic models presented in Fig. 1, are abundant in the literature because of its simplicity and being verified for wide applicability for different types of photovoltaic cells. The bond graph presentation has two different causality assignments. The diode resistance and shunt resistance introduce and uncertainty in the causal structure creating nonlinear problems linked to implicit equations corresponding to conductance causality for $R_d$ in equation 2 and 3, or resistance causality for $R_d$.

$$\begin{cases} V_d = V_T Log\left(\frac{I_d}{I_s}+1\right) \\ I_d = I_{ph} - I_{sh} - \frac{V_d}{R_{sh}} \end{cases} \quad (4)$$

where, $I_{ph}$ is the photocurrent equal to short circuit current $I_{sc}$, $I_s$ is the reverse saturation current of the diode, $V_T$ is the thermal voltage and $I_{sh}$ present the shunt current through the shunt resistance.

To solve the problem of double causality loop, let associate the current source with diode current and replaced by only one flow source. A reduced model was presented in [16] by neglecting the parasitic resistance, which avoids the implicit equations and facilitate considerably the exploitation of photovoltaic generator model for control objectives.

From junction "0" and "1" from causal bond graph presentation of photovoltaic model in Fig.2 and using the bond graph rules [17] to determine the governed equation corresponding to each junction.

Junction "0" $\begin{cases} e_1 = e_2 = e_3 = e_4 \\ f_1 - f_2 - f_3 - f_4 = 0 \end{cases}$ (5)

Junction "1" $\begin{cases} f_4 = f_5 = f_6 \\ e_4 - e_5 - e_6 = 0 \end{cases}$ (6)

The constituting laws of the elements are given by the following equations:

$$f_1 = I_{ph} \quad (7\text{-a})$$

$$f_6 = I_{pv} \quad (7\text{-b})$$

$$f_2 = \frac{e_2}{R_{sh}} \quad (7\text{-c})$$

$$e_6 = V_{pv} \quad (7\text{-d})$$

$$e_5 = R_s I_{pv} \quad (7\text{-e})$$

$$e_3 = V_T Log\left(\frac{f_2}{I_s}+1\right) \quad (7\text{-f})$$

thus

$$e_3 = V_T Log\left(\frac{f_1 - f_2 - f_6}{I_s}+1\right) \quad (8)$$

From the junctions "0" and "1" and the equation (7-c)

$$e_4 = V_T Log\left(\frac{f_1 - \left(\frac{e_5+e_6}{R_{sh}}\right) - f_6}{I_s}+1\right) \quad (9)$$

Then combining equations (7-a), (7-d) and (7-e) leads to the expression of the PV module's output voltage

$$V_{pv} = V_T Log\left( \frac{I_{ph} - \frac{V_{pv}}{R_{sh}} - \frac{R_s I_{pv}}{R_{sh}} - I_{pv}}{I_s} + 1 \right) - R_s I_{pv} \tag{10}$$

From the preview equations, the current $I_{pv}(f_6)$ of photovoltaic can be written as follow

$$I_{pv} = I_{ph} - I_s \left[ \exp\left( \frac{V_{pv} + R_s I_{pv}}{n V_T} \right) - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \tag{11}$$

Mathematics model equations for double diode photovoltaic are:

$$f_1 = I_{ph} \tag{12}$$

first “0” junction

$$f_1 = f_{sh} + f_{d1} + f_2 \tag{13}$$

second “0” junction

$$e_{sh} = R_{sh} f_{sh} \tag{14}$$

$$f_{d1} = I_{s1}\left[ \exp\left( \frac{e_{d1}}{n_1 V_T} \right) - 1 \right] \tag{15}$$

$$f_{d2} = I_{s2}\left[ \exp\left( \frac{e_{d2}}{n_2 V_T} \right) - 1 \right] \tag{16}$$

In the “1” junction

$$e_3 = e_s + e_4 \tag{17}$$

$$e_s = R_s f_s \tag{18}$$

The current of photovoltaic is $f_4$ and the voltage is $e_4$, so the current-voltage equation is:

$$f_4 = Sf + I_{s1}\left[ \exp\left( \frac{e_4 - R_s f_{d1}}{n_1 V_T} \right) - 1 \right] + I_{s2}\left[ \exp\left( \frac{e_4 - R_s f_{d2}}{n_2 V_T} \right) - 1 \right] + \frac{e_4 + R_s f_s}{R_{sh}} \tag{19}$$

$$\begin{aligned} I_{pv}(f_4) &= I_{ph}(Sf) + I_{s1}\left[ \exp\left( \frac{V_{pv}(e_4) - R_s I_{pv}(f_4)}{n_1 V_T} \right) - 1 \right] + \\ & I_{s2}\left[ \exp\left( \frac{V_{pv}(e_4) - R_s I_{pv}(f_4)}{n_2 V_T}{}_s \right) - 1 \right] + \frac{V_{pv}(e_4) + R_s I_{pv}(f_4)}{R_{sh}} \end{aligned} \tag{20}$$

Several researches simplify the single diode model by considering that the shunt resistant is large, and the series resistance is small, and they can be ignored from the photovoltaic model. The new voltage and current from equation (11) and (12) of photovoltaic presented as follow.

$$V_{pv} = V_T Log\left( \frac{I_{ph} - I_{pv}}{I_s} + 1 \right) - R_s I_{pv} \tag{21}$$

$$I_{pv} = I_{ph} - I_s \left[ \exp\left( \frac{V_{pv}}{n V_T} \right) - 1 \right] \tag{22}$$

## 4. Test Simulation

Three technologies of solar cell are choosing to simulate the equation (12) generated by bond graph approach for solar cell and photovoltaic module. The monocrystalline Solar cell RTC France Company and flexible hydrogenated amorphous silicon a-Si:H. Also, the polycrystalline photovoltaic module with 36 solar cells connected in series is simulated. The datasheet parameters of the solar cell and photovoltaic module are given in [18] [19]. The simulated results of current-voltage and power voltage are illustrated in Fig. 7, 8 and 9.

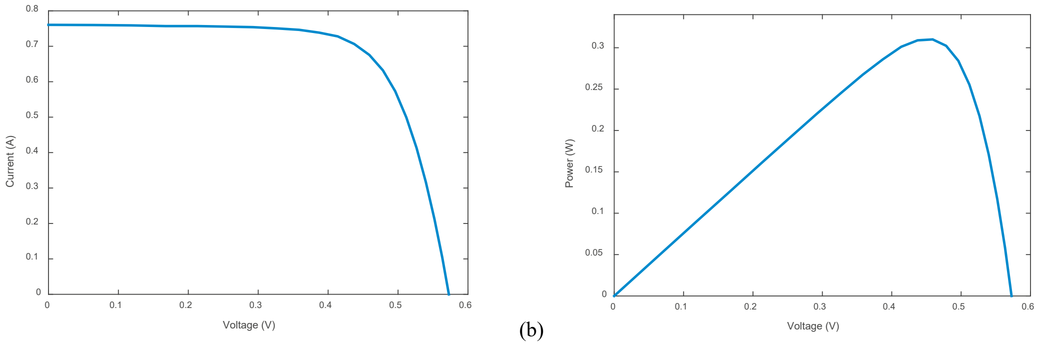


Fig. 7. (a) current-voltage and (b) power-voltage of solar cell RTC France Company.

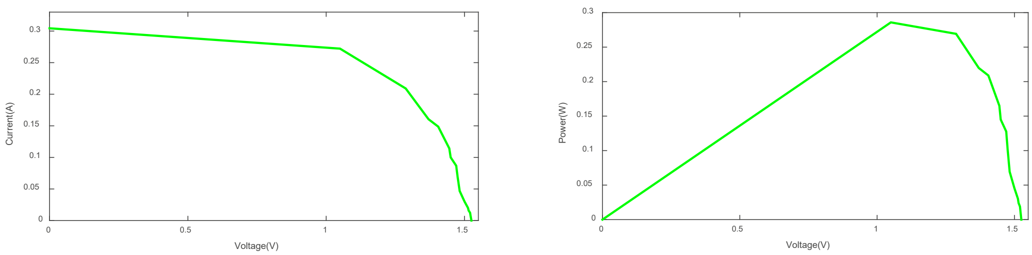


Fig. 8. (a) current-voltage and (b) power-voltage of flexible hydrogenated amorphous silicon a-Si:H photovoltaic cell.

(a) (b)

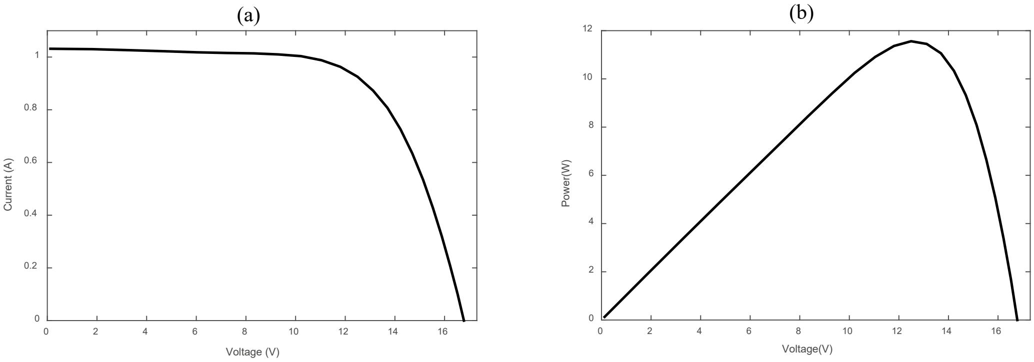


Fig. 9. (a) current-voltage and (b) power-voltage of photovoltaic module with 36 solar cells connected in series.

## 5. Conclusion

The deal of this paper is the modelling of photovoltaic module by dynamical bond graph methodology. The proposed method is evaluated using three sets of solar cell technology; single diode, double diodes and model with capacitance. So, by applying the laws of bond graph approach at 0-and 1-junction we found the generated equations of each model. The equation allows to simulate the models in any software. The simulation results of three tested solar cells and photovoltaic modules show the capability of generated equation of bond graph approach.

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