

# Double-Exponential Model of a Photovoltaic Cell with Temperature Dependence

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**Abstract**—The purpose of the research is the creation of mathematical models in MATLAB based on the double exponential model of the photovoltaic cell. The developed model allows for different physical and environmental parameters. An equivalent circuit of the model includes a photocurrent source, two diodes, and a series and parallel resistance. The paper presents the simulation results for each parameter. The simulation data are displayed graphically and numerical results are saved in a file.

**Keywords:** double-exponential model, photovoltaic cell, Simulink.

## I. INTRODUCTION

MATLAB is a mathematical package of great potential. MATLAB works with matrix data and enables to create a custom calculated program. MATLAB is an operating environment and a programming language. Simulink is a standalone toolbox in MATLAB. Simulink can be used together with the MATLAB and other toolboxes, as well as individually. Simulink implements the principle of visual programming: the user uses the library to construct the model, configures the solver and calculation step. MATLAB/Simulink allows creation of blocks, programs and libraries. MATLAB and Simulink are graphical displays of simulation results.

The paper focuses on the double-exponential model of the photovoltaic cell (PV). The mathematical model is described in section two. Section three considers the model based on the Simulink toolbox. Section four presents the results of the model operating. The results for the effect of solar radiation, the PV cell temperature, diode saturation current, diode quality factor, and serial and parallel resistances are presented.

This study is part of the energy installation model and examines only the work of the photovoltaic. Attention is

paid to the influence of temperature, because the installation will also run with the thermal energy.

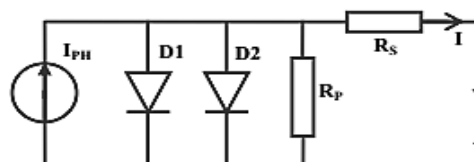


Fig.1. Equivalent circuit for a double-exponential model.

## II. DOUBLE-EXPONENTIAL MODEL OF PV

The circuit (Fig.1) consists of a current source, diodes, and a serial and a parallel resistance. The current source simulates the occurrence of the photocurrent in a cell under illumination. The first diode is connected in forward direction in parallel to the current source. The saturation current can flow through the diode when affected by the bias due to excessive concentrations of electrons in the n- region of the cell and the concentration of holes in its p-region. The parallel photovoltaic cell resistance arises due to the reverse resistance of the n-p-transition and various conductive films or contamination on the cell surface or local small shunts. It is also connected in parallel to the current source. Series resistance represents contacts (mainly semiconductor-metal contact resistance) and the resistance of the semiconductor material from which the solar cell is manufactured (the resistance of each of the p- and n- regions of the cell) [1].

The single diode equation assumes a constant value for the quality factor  $N$ . In actual practice, the quality factor is a function of the voltage across the device. At high voltage, when the recombination in the device is dominating in the surface layer and bulk regions, the quality factor is close to one. At lower voltages, recombination in the junction dominates and the ideality factor approaches two [1]. The mathematical equation of the model is [1]:

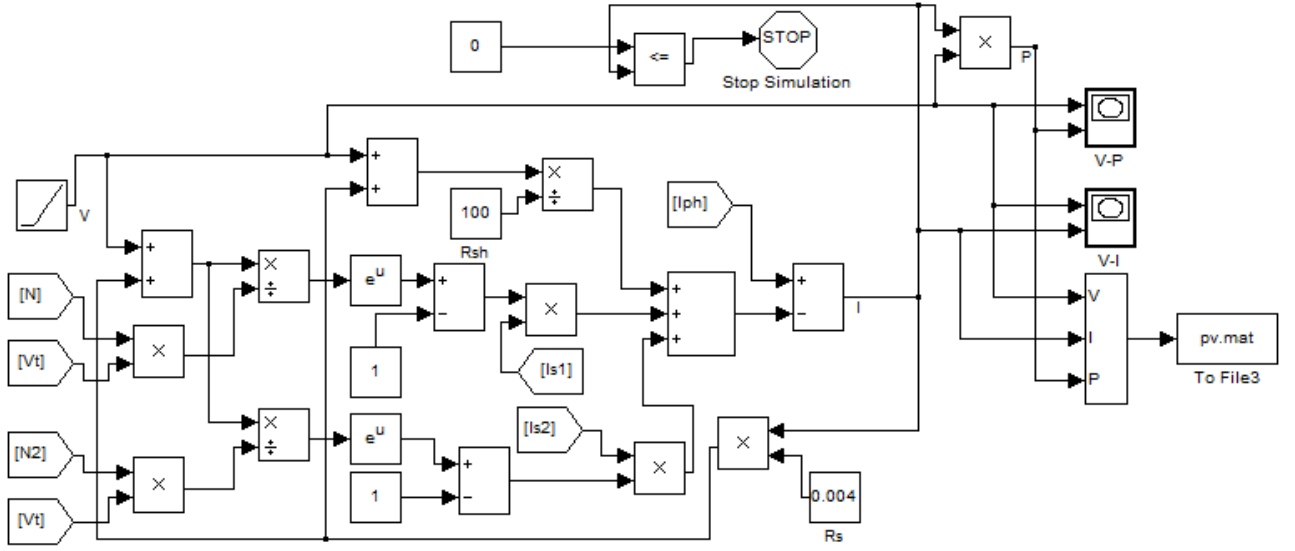


Fig.2. Simulink-model.

$$I = I_{ph} - I_S \left( \exp\left(\frac{V + I \cdot R_S}{N \cdot V_T}\right) - 1 \right) - I_{S2} \left( \exp\left(\frac{V + I \cdot R_S}{N_2 \cdot V_T}\right) - 1 \right) - \frac{V + I \cdot R_S}{R_p}, \quad (1)$$

where

$I_{ph}$  is the solar-induced current;

$I_S$  is the saturation current of the first diode;

$I_{S2}$  is the saturation current of the second diode;

$V_T$  is the thermal voltage;

$N$  is the quality factor (diode emission coefficient) of the first diode;

$N_2$  is the quality factor (diode emission coefficient) of the second diode;

$R_s$  and  $R_p$  are the serial and parallel resistances of the cell;

$V$  is the voltage across the solar cell electrical ports.

The parameters in the double-exponential model depend on the solar radiance and temperature of the cell.

### III. SIMULINK MODEL

The Simulink-model (Fig. 2) implements equation (1) and builds the output V-I and V-P characteristics (Fig.3).

Model features:

The voltage is set by uniformly time-varying signals. The current values are calculated for a definite voltage value at each step. The calculation stops when the current value reaches 0. This function is performed by the block «Stop Simulation». «Stop Simulation» compares the current value with 0 at each calculation step. When reaching the equality, the simulation ends.

The data is stored in the pv.mat file. The data is stored in an array of four lines: the first line is the simulation time, the second line is voltage, the third line is current, and the fourth line is power. The stored data can be loaded in the Workspace for later processing.

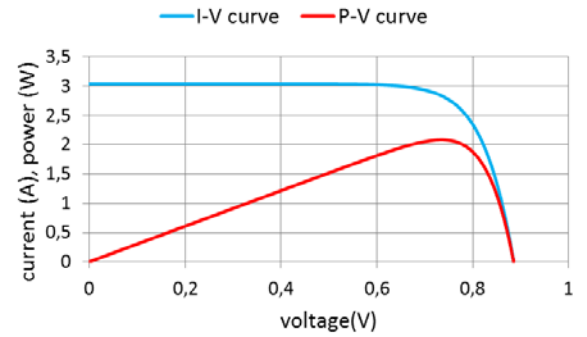


Fig.3. I-V and P-V curves.

## IV. SIMULATION RESULTS

### A. Effect of Solar Radiation Variation

The effect of solar radiation is determined by equation (2) [2][3]:

$$I_{ph} = \frac{S}{1000} \cdot (I_{sc} + K_i(T_c - T_r)), \quad (2)$$

where

$I_{ph}$  is a light-generated current or photocurrent;

$S$  is the value of solar radiation (in  $W/m^2$ , to be inserted without dimension);

$I_{sc}$  is the cell short-circuit current at  $25^\circ C$  and  $1kW/m^2$ ;

$T_c$  is the cell working temperature;

$T_r$  is the cell reference temperature ( $25^\circ C$ );

$K_i$  is a constant which reflects the temperature dependence of the photocurrent (due to the slightly varying bandgap with temperature).

The realization of equation (2) as a subsystem is shown in Fig. 4. The effect of solar radiation is shown in Fig.5.

The effect of the variation of solar radiation on the current of the PV module is greater than that on the voltage.

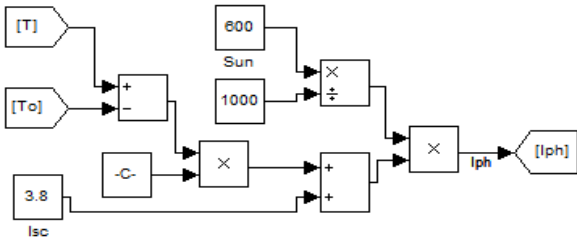


Fig.4. Subsystem realizes Iph.

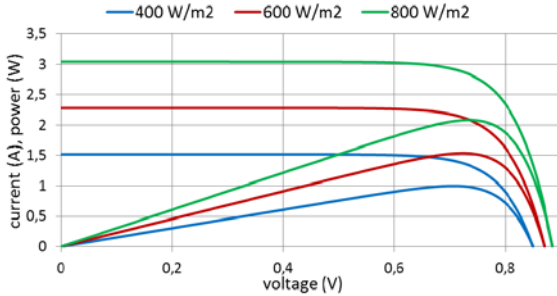


Fig.5. I-V and P-V curves for different solar radiations (S).

**B. Effect of Diode Quality Factor Variation**

As can be seen from equation (1), other conditions being equal, the value of the diode quality factor has the same effect on the result. Therefore, it is important to consider this value as they may be unequal. The results of the simulation are shown in Fig.6.

Reducing the value of the diode quality factor has a significant effect on the PV module voltage. For different values of the diode quality factor for each diode, the voltage is found to decrease as well.

It is generally accepted that N is 1 and N2 is 2 [2][3]. But in real conditions quality factor is dependent on solar cell.

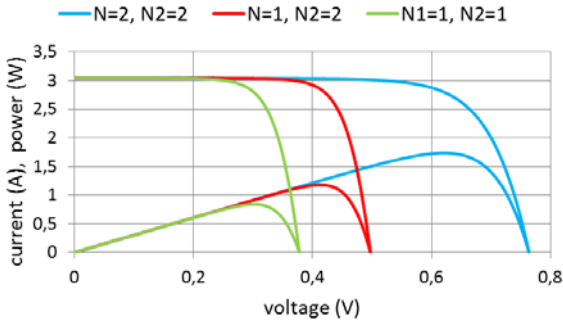


Fig.6. I-V and P-V curves for different quality factors.

**C. Effect of Temperature Variation**

The diode reverse saturation current varies as a cubic function of the temperature [2][3][4] multiplied by an exponential temperature activation expression and it can be expressed as:

$$I_{S1}(T) = I_S \cdot \left(\frac{Tc}{Tr}\right)^{\frac{3}{N}} \cdot \exp\left(\left(\frac{Tc}{Tr} - 1\right) \cdot \frac{E_g}{N \cdot V_T}\right)$$

$$I_{S2}(T) = I_{S2} \cdot \left(\frac{Tc}{Tr}\right)^{\frac{3}{N2}} \cdot \exp\left(\left(\frac{Tc}{Tr} - 1\right) \cdot \frac{E_g}{N2 \cdot V_T}\right), (3)$$

where

$I_S$  is the diode reverse saturation current of fist diode;

$I_{S2}$  is the diode reverse saturation current of second diode;

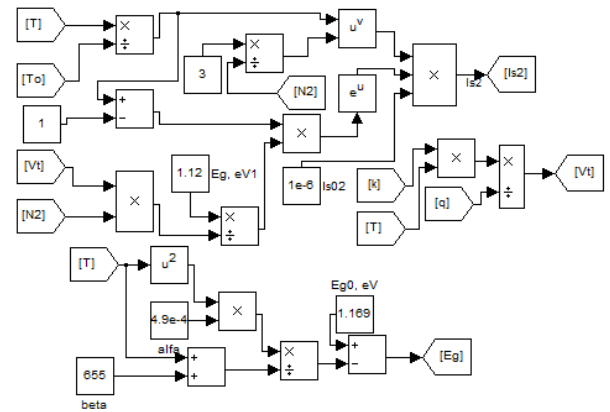


Fig.7. Subsystems realizes temperature depends.

$E_g$  is the band gap energy;

$V_t$  is the thermal voltage ( $V_t = kT_c/q$ , where  $k$  is the Boltzmann constant,  $T_c$  is the cell's working temperature,  $q$  is the elementary charge on an electron);

$N$  is the quality factor (diode emission coefficient) of the first diode;

$N_2$  is the quality factor (diode emission coefficient) of the second diode;

$T_c$  is the cell's working temperature;

$T_r$  is the cell's reference temperature.

The energy gap of silicon as a function of temperature [3] is presented below:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \quad (4)$$

where

$E_g$  is the band gap energy;

$E_g(0)$  is the band gap energy of semiconductor at 0 K;

$\beta$  and  $\alpha$  are is specific value to each semiconductor.

Since this is a double model, the subsystem it used for each diode. In this case, all the diode parameters are equal for both diodes, except the reverse saturation current  $I_{s0}$ , which is generally different from  $I_{s02}$ .

The realization of equations (3) and (4) is shown in Fig.7. The results of the simulation are shown in Fig.8.

The temperature variation has a significant impact on the VI curve and leads to a decrease in energy production. The effect of the temperature on  $V_{oc}$  is one order of magnitude stronger than that on  $I_{sc}$ .

**D. Effect of Diode Saturation Current Variation**

The model enables to predict the behavior of the PV cell for different reverse saturation currents of the diodes.

The results of the simulation are shown in Fig.9.

The variation of the diode saturation current affects significantly  $V_{oc}$ .

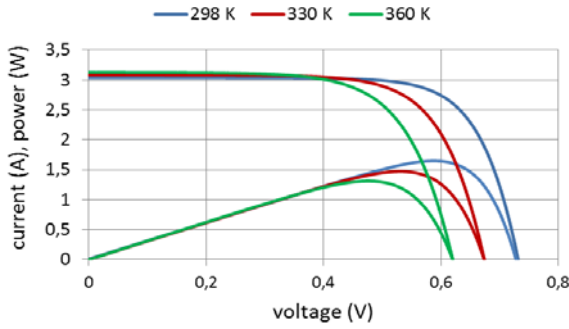


Fig.8. I-V and P-V curves for different temperature.

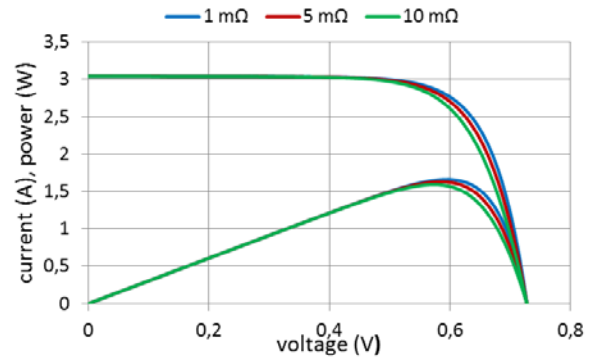


Fig.11. I-V and P-V curves for different Rs.

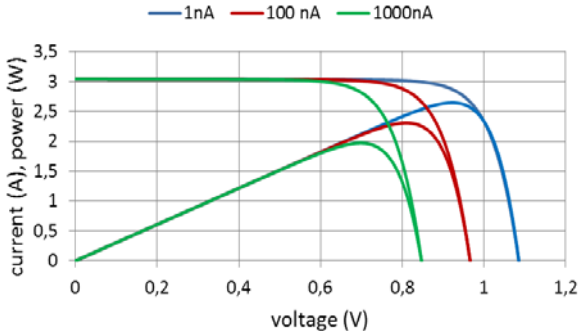


Fig.9. I-V and P-V curves for different value of diode saturation current.

Usually the diode saturation currents of the tow diodes are not equal. This case was simulated and the results are shown in Fig.10.  $I_{s1}$  is varied,  $I_{s2}$  is constant.

As one diode saturation current increases,  $V_{oc}$  decreases, which, in turn, reduces the power output.

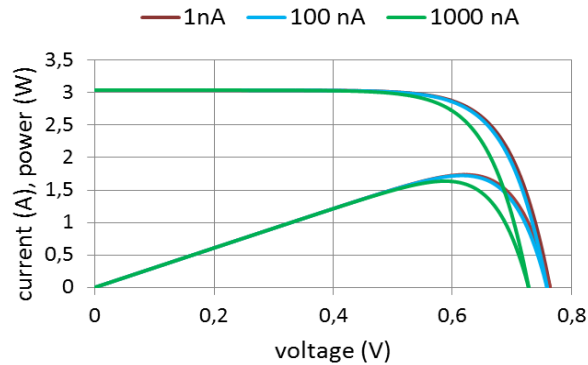


Fig.10. I-V and P-V curves for different values of diode saturation currents.

#### E. Effect of Serial Resistance Variation

The power  $P = IV$  produced by the cell is shown in Fig. 1. The cell generates the maximum power  $P_{max}$  at  $V_m$  voltage and  $I_m$  current, and the fill factor FF [1][4] can be defined as

$$FF = \frac{I_m \cdot V_m}{I_{sc} \cdot V_{oc}} = \frac{P_{max}}{I_{sc} \cdot V_{oc}}$$

The simulation results for  $R_s$  variation are shown in Fig.11.

As can be seen in Fig.11, the variation of  $R_s$  affects the slope angle of the I-V curves resulting in a deviation of the maximum power point. The fill factor appreciably decreases for higher value of  $R_s$ .

#### F. Effect of Parallel Resistance Variation

The parallel resistance of any cell should be large enough for higher power output and fill factor. In fact, for low  $R_p$ , the PV cell current collapses more steeply which means higher power loss and lower fill factor [5].

The simulation results for  $R_p$  variation are shown in Fig.12.

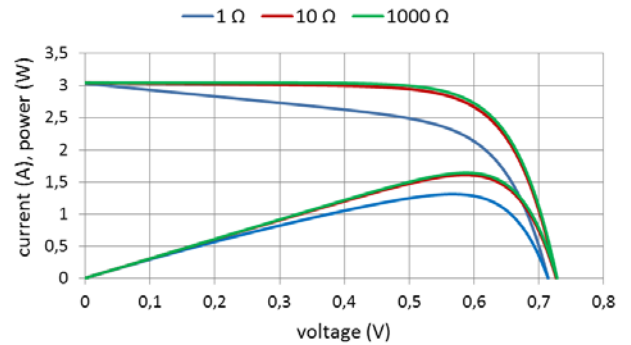


Fig.12. I-V and P-V curves for different  $R_p$ .

### V. CONCLUSION

The Simulink PV model has been created in Simulink toolbox based on the double exponential model of the photovoltaic cell. This model takes into account the non-linearity of PV. The developed model is based on mathematical equations and an equivalent circuit, which includes a photocurrent source, two diodes, series and parallel resistors.

The model for the proposed range of the equivalent circuit elements, irradiance and temperature as model inputs, with the corresponding values of voltages, currents, and power as outputs is presented.

The temperature effect is taken into account when modeling the photocurrent and diode saturation current. Possible differences in the parameters of the diodes in the equivalent circuit are taken into account, as they have a significant impact on  $V_{oc}$  and power output.

Simulation data are displayed graphically and numerical results are saved in a file.

The double-exponential model of a photovoltaic cell with temperature dependence will be used to creation of the energy installation. Accounting for the effects of temperature on the output characteristics is of interest for further work.

#### REFERENCES

- [1] T. Markvart, L. Castafer, "Practical Handbook of Photovoltaics: Fundamentals and Applications," Elsevier Science Ltd. p. 985, 2003.
- [2] Tsai, H., L., Tu, C., S., and Su, Y., J.", "Development of Generalized Photovoltaic Model Using MATLAB/SIMULINK" Proceedings on the world congress on Engineering and Computer Science. 2008, 6p.
- [3] Zhao Ran et al., "A Simplified Double-Exponential Model of Photovoltaic Module in Matlab™," Energy and Environment Technology, 2009. ICEET '09. International Conference on (Volume:3 ) 2009.
- [4] Tarak Salmi et al., "MATLAB/Simulink Based Modelling of Solar Photovoltaic Cell". International journal of renewable energy research 2012, Vol.2, No.2, 6p.
- [5] Savita Nema, R.K. Nema, Gayatri Agnihotri, "MATLAB/Simulink based study of photovoltaic cells / modules / array and their experimental verification," International journal of Energy and Environment, vol.1, No.3, pp.487-500, 2010.