

## Mathematical Modeling and Simulation of Photovoltaic Array

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### ABSTRACT

With the increasing demand of power and depleting resources, PV based power system has been a ray of hope for the future energy scenario. The non-linear V-I Characteristics of PV module depends on solar irradiance and other environmental factors. This paper deals with power electronics based simulation model for photovoltaic integrated module. The model includes the real time behavior of the PV module. Detailed simulink modeling for PV module along with numerical values has been presented. The simulation model has been verified for 36 W PV modules. The proposed model has been found to exhibit better and accurate result for any irradiance and temperature variations

**Keywords** – Photovoltaic Module, Simulink Model, V-I Characteristics

### I. INTRODUCTION

A photovoltaic (PV) module converts solar energy into electrical energy. The basic components of a photovoltaic module include photovoltaic cell, DC-DC converter, storage battery, etc. PV cells includes grouped/individual panels or modules, depending on the requirement and rating of the system under consideration. Panels can be grouped to form large photovoltaic arrays. The term *array* is usually employed to describe a photovoltaic panel (with several cells connected in series and/or parallel) or a group of panels. Most of time one are interested in modeling photovoltaic panels, which are the commercial photovoltaic devices. This paper focuses on modeling photovoltaic modules or panels composed of several basic cells. The term *array* used henceforth means any photovoltaic device composed of several basic cells. In the Appendix at the end of this paper there are some explanations about how to model and simulate large photovoltaic arrays composed of several panels connected in series or in parallel.

### I. Modeling Of Photovoltaic Arra

#### 1.1 Ideal Photovoltaic Cell

Fig. 1 shows the equivalent circuit of the ideal photovoltaic cell. The basic equation from the theory of semiconductors [1] that mathematically describes the I-V characteristic of the ideal photovoltaic cell is:

$$I = I_{pv,cell} - I_{o,cell} \left[ \exp \left( \frac{qV}{akT} \right) - 1 \right] \quad (1)$$

$$I_d = I_{o,cell} \left[ \exp \left( \frac{qV}{akT} \right) - 1 \right]$$

where  $I_{pv,cell}$  is the current generated by the incident light (it is directly proportional to the Sun irradiation),  $I_d$  is the Shockley diode equation,

$I_{0,cell}$  [A] is the reverse saturation or leakage current of the diode [A],  $q$  is the electron charge [ $1.60217646 \cdot 10^{-19}C$ ],  $k$  is the Boltzmann constant [ $1.3806503 \cdot 10^{-23}J/K$ ],  $T$  [K] is the temperature of the  $p-n$  junction, and  $a$  is the diode ideality constant. Fig. 2 shows the I-V curve originated from (1).

#### 1.2 Modeling the Photovoltaic Array

The basic equation (1) of the elementary photovoltaic cell does not represent the I-V characteristic of a practical photovoltaic array. Practical arrays are composed of several connected photovoltaic cells and the observation of the characteristics at the terminals of the photovoltaic array requires the inclusion of additional parameters to the basic equation [1]:

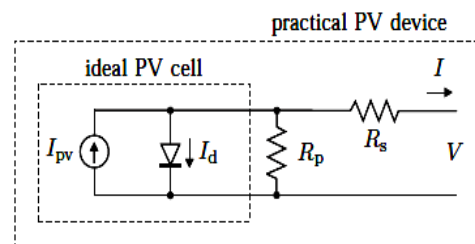


Fig. 1 Single-diode model of the theoretical photovoltaic cell and equivalent circuit of a practical photovoltaic device including the series and parallel resistances.

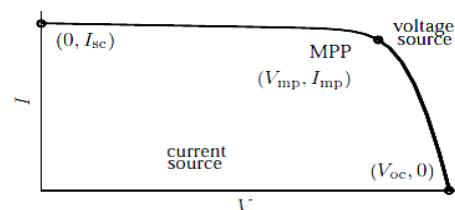


Fig. 2 Characteristic I-V curve of a practical photovoltaic device and the three remarkable points: short circuit (0, Isc), maximum power point (Vmp, Imp) and open-circuit (Voc, 0).

$$I = I_{pv} - I_0 \left[ \exp\left(\frac{V + R_s I}{V_t \alpha}\right) - 1 \right] - \frac{V + R_s I}{R_p} \quad (2)$$

Where  $I_{pv}$  and  $I_0$  are the photovoltaic and saturation currents of the array and  $V_t = N_s k T / q$  is the thermal voltage of the array with  $N_s$  cells connected in series. Cells connected in parallel increase the current and cells connected in series provide greater output voltages. If the array is composed of  $N_p$  parallel connections of cells the photovoltaic and saturation currents may be expressed as:  $I_{pv} = I_{pv, cell} N_p$ ,  $I_0 = I_{0, cell} N_p$ . In (2)  $R_s$  is the equivalent series resistance of the array and  $R_p$  is the equivalent parallel resistance. This equation originates the I-V curve seen in Fig. 3, where three remarkable points are highlighted: short circuit (0,  $I_{sc}$ ), maximum power point ( $V_{mp}$ ,  $I_{mp}$ ) and open-circuit ( $V_{oc}$ , 0). The light generated current of the photovoltaic cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation [6]:

$$I_{pv} = (I_{pv,n} + K_I \Delta T) \frac{G}{G_n} \quad (3)$$

Where  $I_{pv,n}$  [A] is the light-generated current at the nominal condition (usually 25 °C and 1000W/m<sup>2</sup>),  $\Delta T = T - T_n$  (being  $T$  and  $T_n$  the actual and nominal temperatures [K]),  $G$  [W/m<sup>2</sup>] is the irradiation on the device surface, and  $G_n$  is the nominal irradiation. The diode saturation current  $I_0$  and its dependence on the temperature may be expressed by (4) [3]

$$I_0 = I_{0,n} \left(\frac{T}{T_n}\right)^3 \exp\left[q E_g \frac{1}{\alpha k} \left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \quad (4)$$

where  $E_g$  is the bandgap energy of the semiconductor ( $E_g \approx 1.12$  eV for the polycrystalline Si at 25 °C [4], [3]), and  $I_{0,n}$  is the nominal saturation current:

$$I_{0,n} = \frac{I_{sc,n}}{\exp\left(\frac{V_{oc,n}}{\alpha V_t}\right) - 1} \quad (5)$$

with  $V_{t,n}$  being the thermal voltage of  $N_s$  series-connected cells at the nominal temperature  $T_n$ .

### 1.3 Improving the Model

The photovoltaic model described in the previous section can be improved if equation (4) is replaced by:

$$I_0 = \frac{I_{sc,n} + K_I \Delta T}{\exp\left(\frac{V_{oc,n} + K_V \Delta T}{\alpha V_t}\right) - 1} \quad (6)$$

This modification aims to match the open-circuit voltages of the model with the experimental data for a very large range of temperatures. Eq. (6) is obtained from (5) by including in the equation the current and voltage coefficients  $K_V$  and  $K_I$ .

## II. SIMULATION MODELS AND RESULTS OF THE PHOTOVOLTAIC ARRAY

Fig.3 shows the photovoltaic model circuits implemented with MATLAB/SIMULINK (using the SymPowerSystems blockset) circuit models work perfectly and may be used in the simulation of power electronics converters for photovoltaic systems.

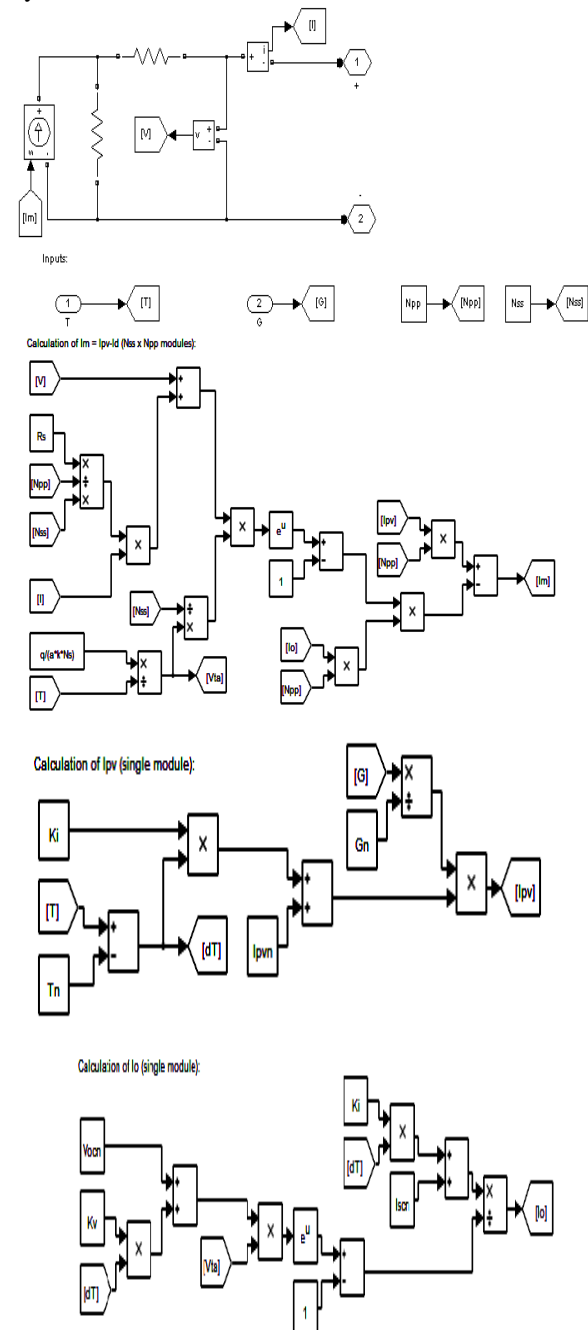
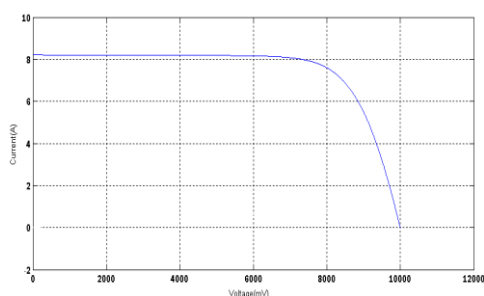
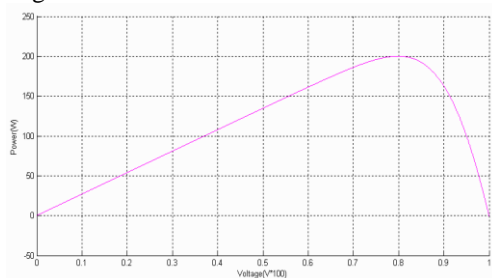


Fig. 3 Photovoltaic Circuit Model built with MATLAB/SIMULINK



I-V curve of solar array plotted by varying voltage applied across the solar array and measuring the corresponding current flowing through it



P-V characteristics Similarly, an accurate P-V curve obtained by varying voltage across the solar array and values of power recorded on X-Y plot as shown in figure

### III. CONCLUSION

This paper has analyzed the development of a method for the mathematical modeling of photovoltaic arrays. The objective of the method is to fit the mathematical I-V equation to the experimental *remarkable points* of the I-V curve of the practical array. The method obtains the parameters of the I-V equation by using : open-circuit voltage, short-circuit current, maximum output power, voltage and current at the maximum power point, current/temperature and voltage/temperature coefficients.

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