Simple Modeling and Simulation of Photovoltaic Panels Using Matlab/Simulink

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Abstract: This paper introduces the simple method of the mathematical modeling and simulation of current-voltage characteristics for photovoltaic panel. The aim of this modeling is to simply the nonlinear I-V model of photovoltaic panel to easily apply the model to the circuit simulators such as SPICE. So this paper is finding the parameters for the nonlinear I-V equations based on only the data such as open circuit voltage, short circuit current, voltage and current at Maximum power point and temperature coefficient for voltage and current at the nominal condition or the standard test condition which are obtained from manufacturer's datasheet.

Keywords: MPP, Modeling, MPPT, Solar panel, Simulation

1 Introduction

The solar radiation seems to be one of the most promising renewable energy sources and can be directly converted into electricity using the photovoltaic(PV) devices, solar cells. Photovoltaic panels are the fundamental power conversion unit. For given environmental conditions, there is Maximum Power Point(MPP), an operating point on the V-I characteristics, where maximum power output is achieved. Therefore, at the MPP the efficiency will be optimized. There are lots of researches about proposing the MPP tracking algorithms and designing the MPP tracker [1,2,3]. The ability to protect output characteristics of a photovoltaic module is very important for the design of MPP tracking and control strategy. Numerous methods have been proposed for modeling the PV panel and extracting the panel's parameters [4-11]. The performance of the PV panels is evaluated under standard test condition(STC), where an average solar spectrum at AM1.5 is used[4], the irradiation of 1000W/cm2 and the module temperature of 25oC.

In this paper, a photovoltaic panel modeling method and simulation will be presented. The parameters for the PV model are based on values provided from the manufacturer's datasheet. The proposed model is similar to a single diode model with a series resistance. But the parameters used in proposed model are obtained from only

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the datasheet measured at STC and the model does not need iteration routine to extract the parameters of I-V characteristics. So, this model is suitable for SPICE modeling and Matlab/Simulink modeling when developing and designing MPPT algorithm. This paper also provides the Simulink modeling of the photovoltaic model performance and some simulation results.

2 Modeling of Photovoltaic Module

The photovoltaic module is a sort of semiconductor diode, whose p–n junction is exposed to light. Basically, the PV phenomenon may be described as the absorption of solar radiation. When the energy of the incident photon is sufficient to detach the covalent electrons of the semiconductor, charges are generated. The incidence of light on the cell generates charge carriers that originate an electric current.

The basic current-voltage characteristics of the PV module can be expressed [5, 6]:

$$= {}_b - {}_0 \left[\ (+ R) - 1 \right] - + \tag{1}$$

where, I and V are the current and voltage of the photovoltaic panel, respectively. $I_{ph}^{(=N_p}{}_{Iph,cell)}$ is the photo-generated current in the PV module consisting of N_p cells connected in parallel. Each cell can generate the photo current of $I_{ph,cell}$. $I_0^{(=N_pI0,cell)}$ is the reverse saturation current of the PV module consisting of N_p cells connected in parallel where each cell has the reverse saturation current of $I_{0,cell}$. V_T $(=aN_s \cdot kT/q)$ is the thermal voltage of the array with N_s cells connected in series where $a(=1.0{\sim}1.5)$ is the ideality factor of the diode, $k(=1.38e\text{-}23\ J/K)$ is the Boltzmann's constant, $q(=1.602e\text{-}19\ C)$ is the electronic charge and T is temperature of the array in Kelvin. R_s is the equivalent series resistance of the PV array. R_p is the equivalent parallel resistance of the PV array.

The practical PV device is operating in a hybrid behavior of current or voltage source depending on the operating point. In the practical PV device, series resistance R_s has strong influence on the performance of PV module when the device operates in the voltage source region, and influence of a parallel resistance R_p will be stronger in the current source region of operation [6]. The value of R_p is generally so high that some authors neglect this resistance to simplify the model [4, 7, 8]. The value of R_s is very low, and sometimes can be neglected too [9, 10].

The photovoltaic array's temperature may be influenced by the solar irradiation and ambient wind speed [11]

$$T = 3.12 + 0.25\ {}_{Sn} + 0.899T_a\text{-}1.3v_a + 273 \tag{2}$$

$_S$

where S and S_n $(=1000W/m^2)$ are the solar irradiation at operating condition and the nominal test condition, respectively, and T_a is the ambient temperature and v_a is

the local wind speed. Equation (2) shows the PV pannel's temperature will be influenced by the solar irradiation and the wind velocity.

The I-V characteristics of the PV devices depend on the internal characteristics of the device(R_s, R_p) and on the external influences such as irradiation level and ambient temperature. The incident light is generating the photo current, which depends linearly on the solar irradiation and is influenced by the temperature[5,6]:

$$_h = (_{h,} + \Delta) \tag{3}$$

where $_{Iph,n}$ is the light generated current at STC and $\Delta T = T - T_n$, T is the panel temperature irradiation, and T_n is the nominal temperature. Because the photo-current is difficult to determine and practically the parallel resistance is high and the series resistance is very small, the assumption $_{Isc \approx Iph}$ is generally used in modeling PV devices.

The open circuit voltage is assumed to be influenced by temperature[7] like

$$= _,(^1 + \Delta) + () \tag{4}$$

where $_{Voc,n}$ is the open circuit voltage measured at the nominal condition and αv is the voltage-temperature coefficient. The datasheets of PV arrays provide a few experimental data about electrical and thermal characteristics. The experimental data from the datasheets are not suitable for I-V curve of PV array such as equation (1). All PV array datasheets give basically the following information: the nominal open-circuit voltage($V_{oc,n}$), the nominal short-circuit current($I_{sc,n}$), the Maximum Power Point (MPP) voltage(V_{mp}), the MPP current(I_{mpp}), the short-circuit current/temperature coefficient(αI), the open-circuit voltage/temperature coefficient(αv), and the experimental peak power(P_{max}), which are measured at the nominal condition or standard test conditions(STC) of temperature $T=298K$ and solar irradiation of S=1000W/m^2. At the STC, the basic equation can be rewritten as

$$= _{h,} - _0, [(_+ \qquad ,) - 1] - _\pm \tag{5}$$

where the subscript n is used to show the fact the values are measured at the STC. It also be assumed that the series resistance and the parallel resistance are independent of the temperature or solar irradiation. Therefore these parameters don't have a subscript n. To simplify the modeling, we further assume the parallel resistance R_p is so large to ignore the third term of eq. (5).

$$I = I_{ph,n} - I_{0,n} [\exp (_{V+R_sI}$$

$$V_{T,n}) -1]$$

(6) The I-V curve of solar cells has three important points: short circuit($0, I_{sc}$), open circuit($V_{oc}, 0$) and maximum power point(V_{mp}, I_{mpp}). At these important points, the equations are:

$$I_{sc,n} = I_{ph,n} - I_{0,n} \left[\exp \left(\frac{R_s I_{sc,n}}{V_{T,n}} \right) -1 \right] \tag{7}$$

$$0 = I_{ph,n} - I_{0,n} \left[\exp \left(\frac{V_o}{V_{T c_n,n}} \right) -1 \right] \tag{8}$$

$$I_{mpp,n} = I_{ph,n} - I_{0,n} \left[\exp \left(\frac{V_{mpp,n} + R_s I_{mpp,n}}{V_{T,n}} \right) -1 \right]$$

The diode saturation current may be expressed in its dependence on the temperature [6],

$$I_0 = I_{0,n} \left(\frac{T_n}{T} \right)^3 \exp \left\{ \frac{q E_G}{ak} \left(T_n^{-1} - T^{-1} \right) \right\} \tag{10}$$

where E_G is the band-gap energy of the PV material. From eq. (8), the diode saturation current at the STC is related to the pho-current at STC,

$$I_{0,n} = \frac{I_{ph,n}}{\left[\exp \left(\frac{V_{oc,n}}{V_{T,n}} \right) \right]_n} \tag{11}$$

The PV model can be improved[6] if (8) is replaced by

$$\frac{, + \Delta}{((, + \Delta)/) - 1} \quad 0 \quad = \quad (\quad 1 \quad 2 \quad)$$

With assumption of $V_{oc,n}/V_{T,n} \gg 1$, $I_{0,n}$ can be reduced as follow:

$$I_{0,n} = I_{ph,n} \exp \left(\frac{V_{oc,n}}{V_{T,n}} \right) \tag{13}$$

From eq. (13) and eq. (6), we can calculate

$$= , \left(1 + _{h,-} \right) - \tag{14}$$

Equation (6) can be further manipulated with assuming $\exp((V + R_s I) / V_{T,n}) \gg 1$ and eq. (13)

$$= , + , \left(1 - \right) - \tag{15}$$

Equation (15) is a simple PV model, which is shown in Figure 2 [7]. The diode of Figure 2 has the reverse saturation current of $I_{ph,n}$ and the thermal voltage of $V_{T,n}$. At MPP, eq. (15) will be expressed as:

$$,-,= \, ,(1-,) - \quad , \tag{16}$$

$$_{h,}$$

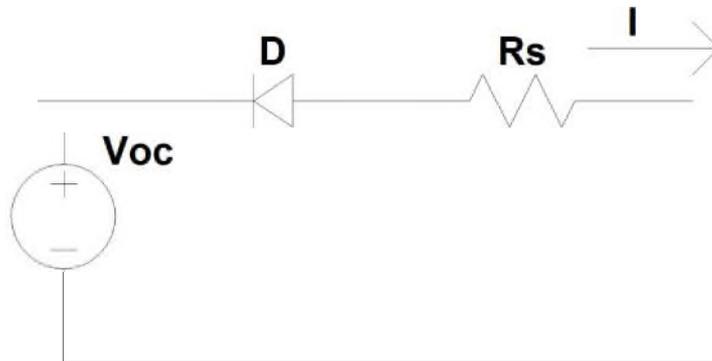**Fig. 1** Equivalent circuit obtained from eq. (15)

On the other hand, at MPP, the derivative of the power with the current will be zero,

$$\big|= () \qquad\qquad \big|= + \big|= 0 \tag{17}$$

And

$$- \, ,$$

$$+ \,,(1 - _{h,}) - \tag{18}$$

So, from these equations we can obtain

$$= \,, + \,,(1 - _{h,}) - \tag{19}$$

Solving eq. (16) and (19), we can get the parameters in the photovoltaic model

$$\tag{20}$$

$$\frac{(,-,}{(\quad)+ \quad - }$$

$$_{2,-,)}$$

$$, =$$

$$= \,, - \frac{,,}{,,-,} \tag{21}$$

The series resistance is assumed to be independent on the cell temperature but thermal voltage is depending on the panel temperature so that the thermal voltage at the panel temperature T can be calculated as:

$$= ,$$ (22)

where $V_{T,n}$ is the thermal voltage of the module at the standard temperature and $T_n=298K$ is the cell temperature at STC.

3 Simulink Modeling and Simulation

The model of PV panel is implemented with Matlab/Simulink. Its input is the ambient conditions like ambient temperature and solar irradiation and its output will be the panel current-voltage characteristics and panel parameters(the thermal voltage and the series resistance). This model needs the parameters from the manufacturer's datasheet measured under standard test condition, such as open circuit voltage, maximum power point voltage voltage-temperature coefficient, short circuit current, maximum power point current and the current-temperature coefficient at STC.

Figure 2 is the detailed diagram of the PV module model. This diagram has two sub-blocks, one is for calculating the thermal voltage and the series resistance at STC and the other is for parameters compensating with the panel temperature and solar irradiation.

Table 1. Parameter of KC200GT solar array at STC

Open circuit voltage	,	32.9V
Voltage at MPP	,	26.3V
Short Circuit Current	,	8.21A
Current at MPP	,	7.61A
Voltage-Temperature Coef.		-0.123V/K
Current-Temperature Coef.		0.0032A/K
Maximum Power, exp	,	200.143W

In order to show the validity of the model, a comparison with other experimental data is very useful. In Figure 3, the I-V characteristics of the photovoltaic panel, KC200GT from KYOCERA [12], are shown where comparing the calculated results with the experimental ones at the temperature of 25oC. In this figure, the solid line is representing the calculated results and circles are the experimental data. The parameters of the KC200GT solar array at the nominal condition are shown in Table 1.
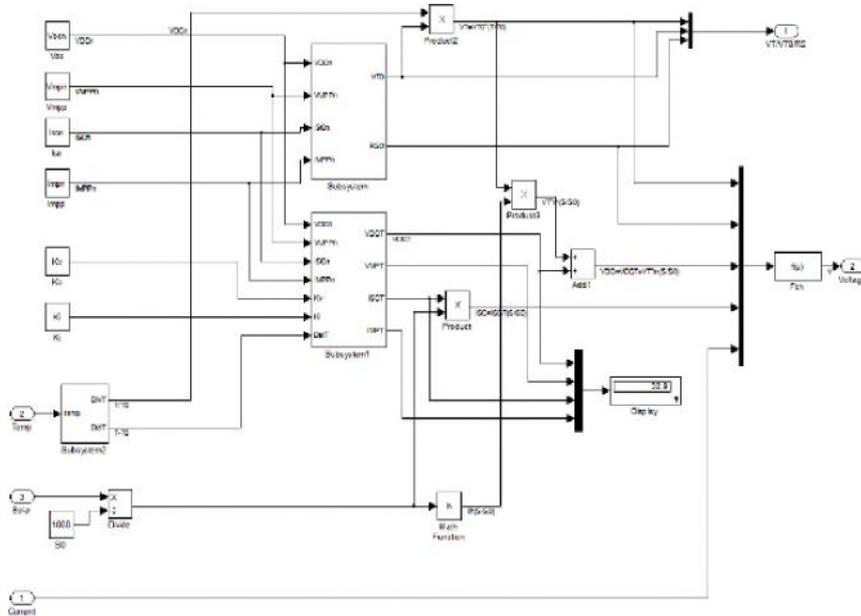
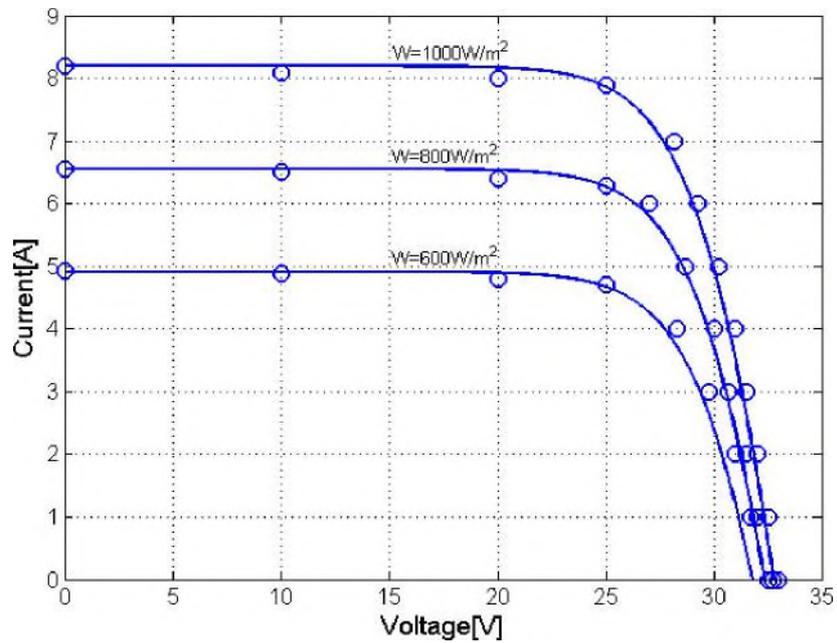**Fig. 2** Solar Cell Modeling with Simulink/Matlab

Fig. 3 The I-V characteristics and experimental data of the KC200GT at array ambient temperature of 25°C

4 Conclusion

In this paper, the mathematical modeling of photovoltaic panel is developed. The purpose of this modeling is to simply the mathematical I-V model of photovoltaic panel to easily apply the model to the circuit simulators such as SPICE. The proposed model uses only the data such as open circuit voltage, short circuit current, voltage and current at Maximum power point and temperature coefficient for voltage and current obtained from manufacturer's datasheet at the nominal condition or the standard test condition. The model in this paper is very simple and has no iteration process, which makes model complex and time consuming. This model can be suitable for circuit simulator and the modeling and simulation of the MPP tracker including solar pannel. In this paper, we also introduce the Matlab/Simulink model and simulated results of the solar panel based on the model. The results from simulation are compared with the experimental results to show the validity of our model.

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