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Photovoltaic module parameters acquisition model

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ABSTRACT

This paper presents basic procedures for photovoltaic (PV) module parameters acquisition using MATLAB and Simulink modelling. In first step, MATLAB and Simulink theoretical model are set to calculate *I–V* and *P–V* characteristics for PV module based on equivalent electrical circuit. Then, limited *I–V* data string is obtained from examined PV module using standard measurement equipment at standard irradiation and temperature conditions and stated into MATLAB data matrix as a reference model. Next, the theoretical model is optimized to keep-up with the reference model and to learn its basic parameters relations, over sparse data matrix. Finally, PV module parameters are deliverable for acquisition at different realistic irradiation, temperature conditions as well as series resistance. Besides of output power characteristics and efficiency calculation for PV module or system, proposed model validates computing statistical deviation compared to reference model.

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1. Introduction

PV module, consisting of defined PV cells in series or parallel connection, represents basic essential power unit for solar energy conversion into electrical energy using photovoltaic effect. Solar photons bring their energy greater then band-gap energy into thin film semiconductors junction and create proportional quantity of electron–hole pairs to conduct the electrical current [2–5,13]. Besides of incident irradiation intensity, the material wafer band-gap energy determines electrical current value a lot [4,6,7]. While higher photons energy causes particles recombination and extinction of some pairs, lower photons energy causes energy transmission and temperature changes into material. However, PV module temperature status, material temperature coefficients, surface/internal material structures and internal impedances influence on output electrical current volume, too. Due to nonlinear *I–V* characteristics of any PV module, it is necessary to simulate and design it for maximum power or efficiency [6,9,13].

Real PV module can be measured using solar simulator equipment in the laboratory at known both irradiance intensity and irradiance spectra [3–6,12,13]. Nevertheless, sparse *I–V* characteristics obtained in split measured points lead to inaccuracy of both *P–V* characteristics and efficiency calculation. Moreover, such experimentation in the laboratory is highly time consuming and costly. To overcome these problems, simulation techniques are used to simulate the behaviour of PV cells or modules under different conditions. Computer modelling is to fill in discontinuities over *I–V* and *P–V* characteristics, gaining in real PV module sparse data matrix approximation and optimization. Consequently, PV module parameters can be obtained from accurate computer model [1,2,6–11,13,14] at any realistic conditions.

The objective of this paper is to present PV module computing model that can simulate *I–V* and *P–V* parameters acquisition at acceptable fidelity to real PV module. Based on reference sparse matrix of precise laboratory measured data obtained from real PV module, the computing model must estimate PV module behaviour at whole range of realistic irradiation intensity, temperature and series resistance conditions. This goal leads to *I–V* and *P–V* characteristics estimate and, efficiency estimate, for any PV cell, module, panel or system. Next goal is achievement of best fit function of *I–V* characteristics via least square method [15]. Then, accuracy of proposed estimation is valued via goodness-of-fit parameter, the standard deviation.

2. Electrical and mathematical model

A PV cell, an elementary PV electrical energy source, stands for equivalent electrical circuit of general five-parameter model [4–6,8,9,11,14], Fig. 1. Since the output terminal current I_0 flowing throw the series resistance R_s (it represents highly resistive emitter and output contacts resistance) consists of initial PV light-generated current I_L, internal leakage current I_p (flowing throw

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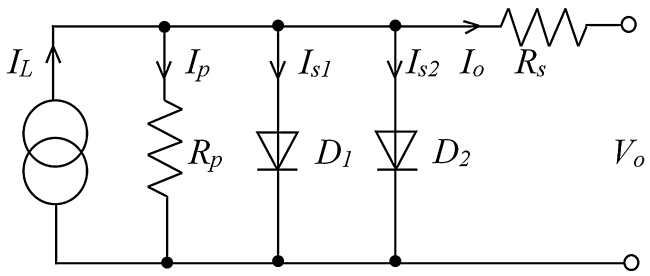

Fig. 1. Equivalent electrical circuit of five-parameter model of PV cell – general model.

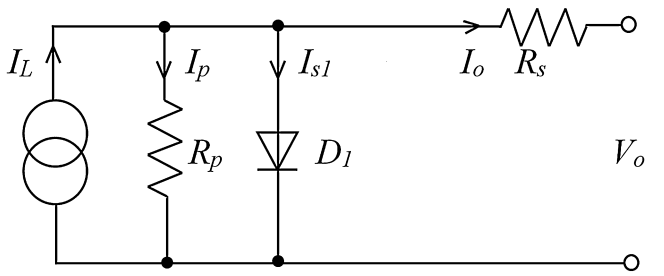

Fig. 2. Equivalent electrical circuit of five-parameter model of PV cell – simplified single-diode model.

parallel resistance R_p or, across the p–n layers junction), diffusion saturation current I_{s1} and re-combination saturation current I_{s2}, it can be expressed as

$$I_0 = I_L - I_{s1} - I_{s2} - I_p \quad [\text{A}]. \tag{1}$$

Here [1,4–7,10–14], initial PV light-generated current I_L is a function of incident solar irradiation λ per unit of surface S (compared to standard condition at irradiation of 1000 W/m^2 at reference temperature T_r = 298.15 K), operational cell temperature T and temperature coefficient K_i by short circuit current I_{sc} at standard conditions (I_{sc} = 0.0017 A/°C). Then, initial PV light-generated current I_L is given by photocurrent [6,10–12] at standard conditions as follows:

$$I_L = \frac{[I_{sc} + K_i(T - 298.15)]\lambda}{1000} \quad [\text{A}]. \tag{2}$$

Diffusion saturation current I_{s1} represents photocurrent losses; it depends on charge carrier diffusion in p–n layers (it can be obtained experimentally), diode ideality factor A [1,2,6–10] (usually, $A \sim 1$), standard material band gap energy E_{g0} (for silicon, E_{g0} = 1.1242 eV) which can change due to temperature changes, electron charge q (q = 1.6022 × 10^{-19} C), Boltzmann's constant k (k = 1.380658 × 10^{-23} J/K) and it can be expressed [1,2,7,10–13] as

$$I_{s1} = I_{sc}\left[\frac{T}{T_r}\right]^3 \exp\left[\frac{qE_{g0}}{kA}\left(\frac{1}{298.15} - \frac{1}{T}\right)\right] \quad [\text{A}]. \tag{3}$$

Similarly, re-combination saturation current I_{s2} represents photocurrent losses depending on charge carrier re-combination k_r in p–n layers (it can be obtained experimentally) and diode ideality factor B (usually, $B \sim 2$); it can be expressed [6,11,14] as

$$I_{s2} = k_r\left[\frac{T}{T_r}\right]^3 \exp\left[\frac{qE_{g0}}{kB}\left(\frac{1}{298.15} - \frac{1}{T}\right)\right] \quad [\text{A}]. \tag{4}$$

Internal leakage current I_p depends on internal resistive losses R_p over output voltage V_0 and series resistance R_s (widely accepted approximation: $R_s \sim I_{sc}/40$, where I_{sc} is the short circuit current at standard conditions); internal leakage current [1,2,6,9,12,14] is given by

$$I_p = \frac{V_0 + I_0 R_s}{R_p} \quad [\text{A}]. \tag{5}$$

According to Shockley theory, re-combination saturation current I_{s2} can be omitted and two-diode model becomes to simplified single-diode model [3,5,8,11,14], Fig. 2.

However, it had better to improve fitting of induced internal leakage current given by simple Eq. (5) to non-linear processes at p–n junction. Thus, depending on saturation current density (mA/cm^2 where short circuit current I_{sc} presents maximum of saturation current over p–n junction area), for number series modules N_s, reverse saturation current I_{rs} [1–3,11,12] is

$$I_{rs} = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{N_s kAT} - 1\right)} \quad [\text{A}] \tag{6}$$

and output terminal current I_0 becomes [1,2,6,7,9,12,14] from Eq. (1) to

$$I_0 = I_L - I_{s1} - I_{rs} \quad [\text{A}]. \tag{7}$$

If PV module or panel consists of identical PV cells in series connection (here, N_s is the number of series PV cells) and, PV power station system consists of identical PV panels (here, N_p is the number of parallel PV panels), overall produced output current of PV system I_{PV} [11,13] can be expressed as

$$I_{PV} = N_p I_L - N_p I_0 \left[\exp\left(\frac{qV_{PV} + I_{PV}R_s}{N_s kAT}\right) - 1\right] \quad [\text{A}] \tag{8}$$

Besides of I–V curves, effectiveness characteristics like overall output power of PV power station might be required. Such characteristics should estimate trends of output electrical power all over the conditions range. Here, a fill factor FF coefficient [3–6,8] performs effective help for electrical efficiency computing using following equation:

$$FF = \frac{kT}{qV_{oc}} \cdot \frac{(W[z] - 1)^2 \exp(W[z] - 1)}{\exp\left(\frac{qV_{oc}}{kT}\right) - 1} \quad [-], \qquad z = \exp\left[1 + \frac{qV_{oc}}{kT}\right]. \tag{9}$$

In (9), Lambert W-function $f(W) = We^W$ is used.

Generally, fill factor represents percentage portion of power volumes: maximum electrical power $P_{\max}$ achievable at defined conditions (i.e., tip of defined curve of PV characteristics or, product of voltage $V_{\max P}$ and current $I_{\max P}$ obtained at maximum power over actual measurement conditions) is referred to idealistic maximum electrical power (i.e., referred to product of maximum open circuit voltage V_{oc} and maximum short circuit current I_{sc}):

$$FF = \frac{P_{\max}}{V_{oc}I_{sc}} = \frac{V_{\max P}I_{\max P}}{V_{oc}I_{sc}} \quad [-]. \tag{10}$$

Fill factor is strongly influenced by recombination currents and intrinsic ohmic resistances. Maximum electrical power $P_{\max}$ at the output of PV power system and solar-to-electrical power conversion efficiency η_p can be expressed [3–6,13] using fill factor FF as follow:

$$P_{\max} = V_{\max P}I_{\max P} = V_{oc}I_{sc}FF \quad [\text{W}], \tag{11}$$

$$\eta_p = \frac{V_{oc}I_{scr}FF}{\lambda} \quad [\%]. \tag{12}$$

3. PV module modelling and results

Firstly, based on the above equations, the script (*.m file with source code) was written in MATLAB v7.11.1 and the block model was set, Fig. 3, in Simulink. Input parameters are set either into MATLAB script (mainly specific data like constants, specific PV module parameters like open circuit voltage V_{oc}, short circuit current I_{sc}, reference sparse matrix, etc.) or by input blocks (in

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